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US Army Corps
of Engineers

Waterways Experiment
Station

Final Report
CPAR-SL-93-1
July 1993

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Investigation of Modified Sulfur Concrete as a Structural Material

by

Michael I. Hammons, Donald M. Smith, Dan E. Wilson, C. Scott Reece

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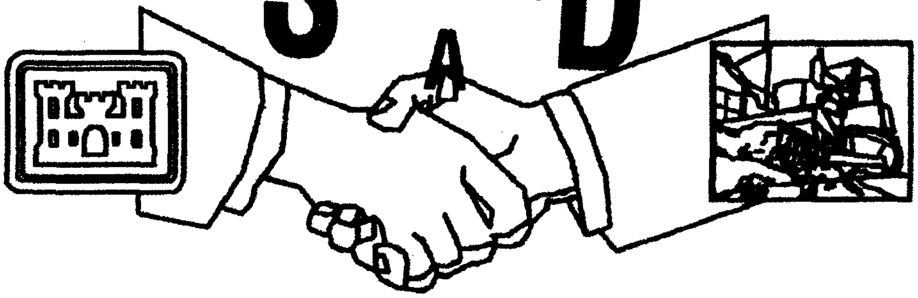

**A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs**

Construction Productivity Advancement Research Program

Technical Report CPAR-SL-93-1
July 1993

Investigation of Modified Sulfur Concrete as a Structural Material

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Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

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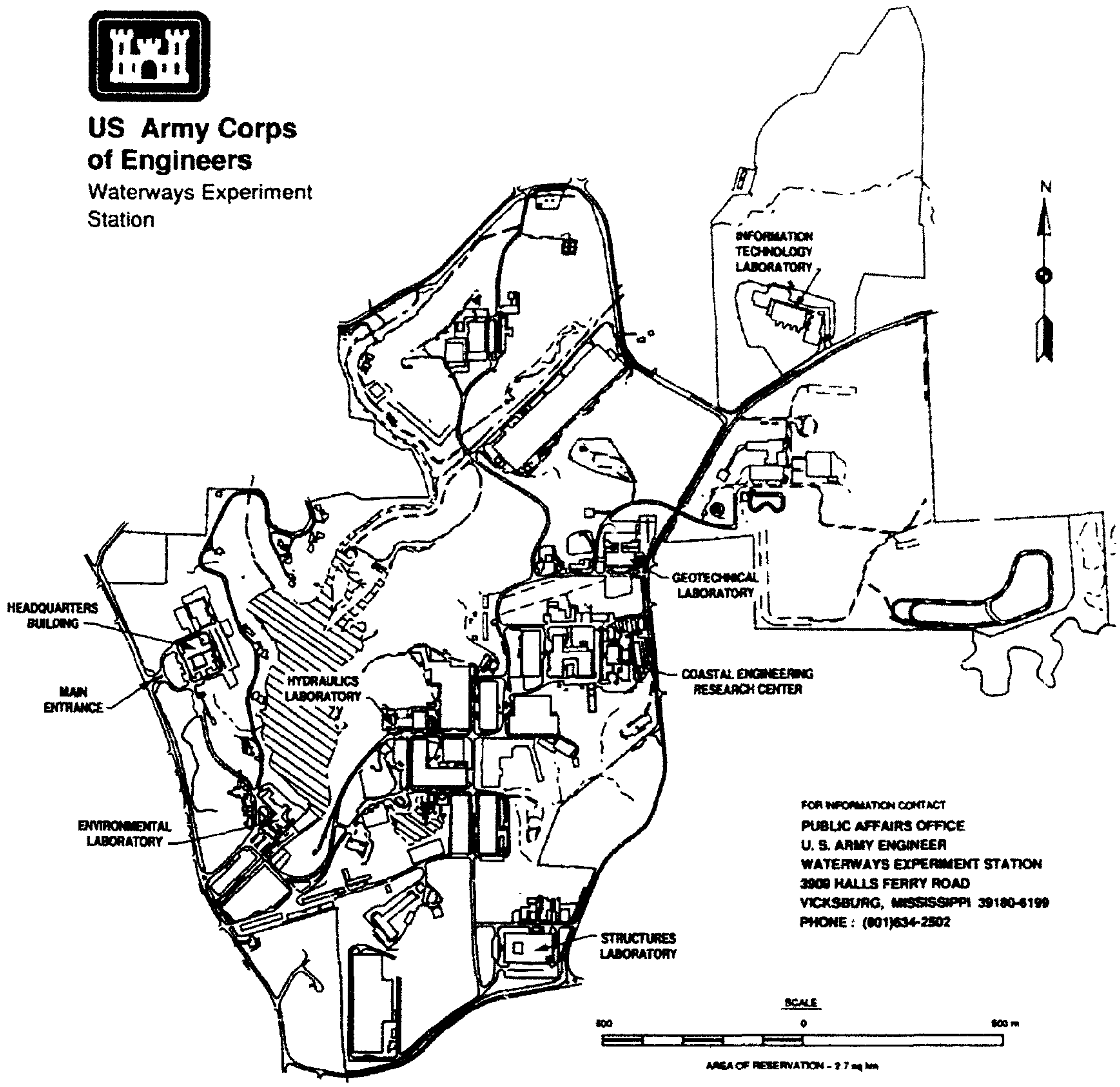

Waterways Experiment Station Cataloging-in-Publication Data

Investigation of modified sulfur concrete as a structural material / by Michael I. Hammons ... [et al.] ; prepared for U.S. Army Corps of Engineers.

62 p. : ill. ; 28 cm. — (Technical report ; CPAR-SL-93-1)

Includes bibliographical references.

1. Concrete construction — Materials — Testing. 2. Strength of materials. 3. Concrete — Additives. 4. Concrete — Mechanical properties. I. Hammons, Michael I. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Construction Productivity Advancement Research Program. V. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; CPAR-SL-93-1.

TA7 W34 no.CPAR-SL-93-1

Contents

Preface

The investigation described in this report was conducted for the Headquarters, U.S. Army Corps of Engineers (HQUSACE), by the U.S. Army Engineer Waterways Experiment Station (WES) in cooperation with National Chempruf Concrete, Inc., Clarksville, TN. This cooperative research and development agreement was a part of the Fiscal Year 1989 Construction Productivity Advancement Research (CPAR) Program. The CPAR Technical Monitors were Dr. Tony Liu and Mr. Daniel Chen.

The testing was performed at WES by members of the staff of the Structures Laboratory (SL), under the general supervision of Messrs. Bryant Mather, Director; J. T. Ballard, Assistant Director, SL; and K. L. Saucier, Chief, Concrete Technology Division (CTD). Mr. William F. McCleese, CTD, was CPAR Program Manager at WES. Direct supervision was provided by Mr. Steven A. Ragan, Chief, Engineering Mechanics Branch (EMB), CTD. This report was prepared by Messrs. Michael I. Hammons, Donald M. Smith, and Dan E. Wilson, EMB, and by Mr. C. Scott Reece, National Chempruf Concrete, Inc. The authors wish to acknowledge Messrs. Andy Shirley, Brent Lamb, Billy Neeley, and Percy Collins, EMB, CTD, for their assistance during this investigation.

At the time of preparation of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	metres
inches	25.4	millimetres
kip-inches	112.9848	newton-metres
kips (force)	4.448222	kilonewtons
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use $K = (5/9)(F - 32) + 273.15$.

1 Introduction

Background

Research and development efforts of the U.S. Bureau of Mines and the Sulfur Institute, followed by additional research and development efforts of National Chempruf ® Concrete, Inc.,[1] Clarksville, TN, have resulted in commercial placement of modified sulfur concrete (MSC) in hostile industrial environments. Industrial applications have been extremely successful in areas of high corrosive activity such as load-bearing floors, walls, and sumps of chemical plants. However, there has been no research and development effort involving the use of this high-strength, corrosion-resistant material in the very demanding structural component field. Designers require extensive structural test results to establish the confidence necessary to specify MSC as a structural material in any major structure.

To address these questions, National Chempruf Concrete, Inc., and the U.S. Army Engineer Waterways Experiment Station (USAEWES) entered into a Cooperative Research and Development Agreement (CRDA) under the Construction Productivity Advancement Research (CPAR) Program. The CPAR program, aimed at helping the United States construction industry improve productivity, is a cost-shared research, development, and demonstration program undertaken by the U.S. Army Corps of Engineers. By advancing the productivity and competitiveness of the United States construction industry, savings in construction costs for the Government will be realized, and the U.S. economy will be boosted. This document is the final report of the work undertaken under Fiscal Year 1989 CPAR Work Unit 32610.

Objective

The objective of this study was to determine the applicability of MSC to the construction and repair of structural components and load-bearing surfaces.

[1] National Chempruf ® Concrete, Inc. is a consortium of companies licensed by the U.S. Department of Commerce to use modified sulfur cement.

Scope

To meet the objective, a series of tests was conducted on MSC to determine the following:

a. Basic mechanical properties important to structural design.

b. Freezing and thawing performance data.

c. Bonding of MSC to portland-cement concrete (PCC).

d. A series of limited reinforced MSC beam tests to compare with PCC structural design criteria. A test matrix is given in Table 1.

Under the terms of the CPAR-CRDA, WES performed the series of tests given in Table 1. All tests were conducted in accordance with the referenced procedures, (American Society for Testing and Materials (ASTM) 1992; USAEWES 1949) in as much as possible, realizing that these methods were developed for PCC or other hydraulic-cement concretes. In some instances, the standard methods were modified to adapt to special test requirements of this test program. All instrumentation was provided by WES, and all data from the tests were reduced and analyzed by WES.

Under the terms of the CPAR-CRDA, all test specimens were cast by National Chempruf Concrete, Inc., in molds which were furnished and prepared by WES. All MSC materials including cement and aggregates were furnished by National Chempruf Concrete, Inc.

Table 1
Test Matrix

Test Description	Specimen Geometry, in. (mm)[1]	Applicable Standard[2]
Compressive Strength	4 × 8 (100 × 200) Cylinder	ASTM C 39
Elastic Modulus	4 × 8 (100 × 200) Cylinder	ASTM C 469
Poissons's Ratio	4 × 8 (100 × 200) Cylinder	ASTM C 469
Splitting Tensile Strength	4 × 8 (100 × 200) Cylinder	ASTM C 496
Pulse Velocity	4 × 8 (100 × 200) Cylinder	ASTM C 597
Fundamental Transverse Frequency	4 × 8 (100 × 200) Cylinder	ASTM C 215
Bond Strength	6 × 12 (150 × 300) Cylinder	ASTM C 882
Resistance to Rapid Freezing and Thawing	3½ × 4½ × 16 (90 × 115 × 406) Beam	ASTM C 666
Long-Term Durability	6 × 6 × 36 (150 × 150 × 915) Beam	Treat Island
Creep in Compression	6 × 16 (150 × 400) Cylinder	ASTM C 512
Tensile Strain Capacity	12 × 12 × 66 (300 × 300 × 1,680) Beam	CRD-C 71
Beam Tests	12 × 12 × 66 (300 × 300 × 1,680) Beam	ASTM C 78

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.
[2] Complete reference information for the applicable standards is given in the list of references following the main text of this report.

2 Concrete Mixture

General

Sulfur concrete is very similar in composition to PCC except that sulfur cement and fly ash are substituted for the portland cement-water paste as shown in Figure 1. The sulfur cement, which was developed by the U.S. Bureau of Mines, is a sulfur that has been chemically modified to produce a thermoplastic polysulfide-sulfur blend. This polymerization imparts durability to the sulfur. Sulfur concrete is batched hot between 260 °F (127 °C and 285 °F (140 °C). At this temperature, the melted sulfur cement provides fluidity to the mixture. Upon cooling, the mixture develops its mechanical properties.

American Concrete Institute (ACI) Committee 548, Polymers in Concrete, has published ACI 548.2R, "Guide for Mixing and Placing Sulfur Concrete in Construction." The reader is referred to this document for more details on this aspect of sulfur concrete construction (ACI 1992b).

Mixture Proportions

The mixture proportions (by mass) for the mixture used in this study were as follows:

45.9% coarse aggregate
34.6% fine aggregate
11.5% sulfur cement
8.0% Class F fly ash

The coarse aggregate was an ASTM C 33, size designation #67, crushed limestone, and the fine aggregate was a natural river sand. Gradings of the aggregates are given in Table 2. For the coarse aggregates, salt-resistant limestone was chosen rather than acid-resistant quartz, because it was more readily available. The sulfur cement used was produced in accordance with the U.S. Bureau of Mines specifications.

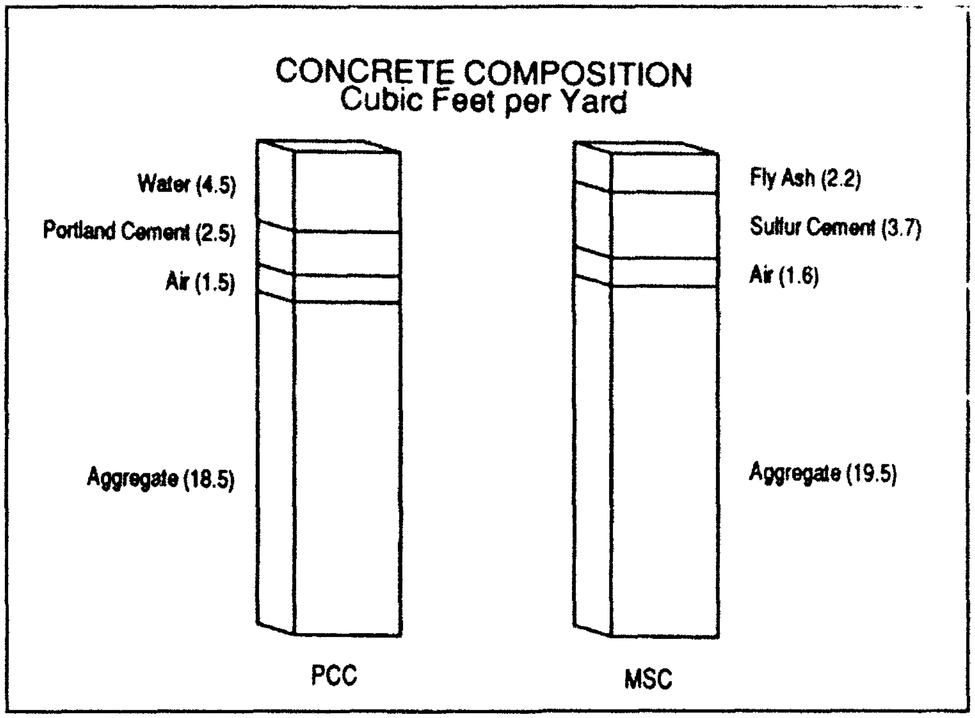

Figure 1. Comparison of composition of typical PCC and MSC

Table 2
Aggregate Gradings

Sieve Size	Cumulative Percent Passing	
	Coarse Aggregate	Fine Aggregate
19.0 mm (3/4 in.)	94.7	
12.5 mm (1/2 in.)	36.8	
9.5 mm (3/8 in.)	17.5	
4.75 mm (# 4)		98.4
2.36 mm (# 8)		90.8
1.18 mm (# 16)		77.2
600 μm (# 30)		56.1
300 μm (# 50)		10.3
150 μm (# 100)		1.0
75 μm (# 200)		0.4

Specimen Casting

All specimen molds were prepared at WES and shipped to National Chempruf Concrete, Inc., for casting. All batching was done in a specially designed, truck-mounted mixer capable of maintaining a temperature of 270 °F (132 °C). The day of casting, all aggregates were weighed and preheated to 270 °F (132 °C). The preheated aggregates, sulfur cement, and fly ash were then batched in the truck.

The fluid MSC mixture was placed in the forms using external vibration. External heat was applied to the molds and concrete when difficulty in finishing the concrete specimens was encountered. The resulting finish of the beam surfaces was rough and uneven. Therefore, when placing MSC in metal forms, the forms should be preheated to prevent rapid heat loss from the MSC and a corresponding reduction in workability.

3 Mechanical Properties Tests

General

A number of basic mechanical properties tests were conducted as listed in Table 1. These tests provided data required to characterize essential mechanical response features of the MSC mixture provided by National Chempruf Concrete, Inc. The results of these tests are described in the following paragraphs.

Compressive Strength, Elastic Modulus, Poisson's Ratio

Compressive strength tests were conducted in accordance with ASTM C 39 (ASTM 1992) on three 4- by 8-in. (100- by 200-mm) cylindrical specimens. The results of these tests are given in Table 3. The specimens were strain gaged, and strain data were obtained during the tests. From the applied load and measured strain data, stress-strain curves were plotted. These data are shown in Figure 2. Using these data, the elastic modulus and Poisson's ratio were calculated in accordance with ASTM C 469 (ASTM 1992). The results of these calculations are also given in Table 3.

Table 3
Results of Compression Tests

Specimen	Compressive Strength		Modulus of Elasticity		Poisson's Ratio
	psi	MPa	million psi	MPa	
MP-1	8,040	55.4	4.70	32,400	0.22
MP-2	8,520	58.8	5.15	35,500	0.26
MP-3	7,240	49.9	4.25	29,300	0.23
Mean	7,940	54.7	4.70	32,400	0.24

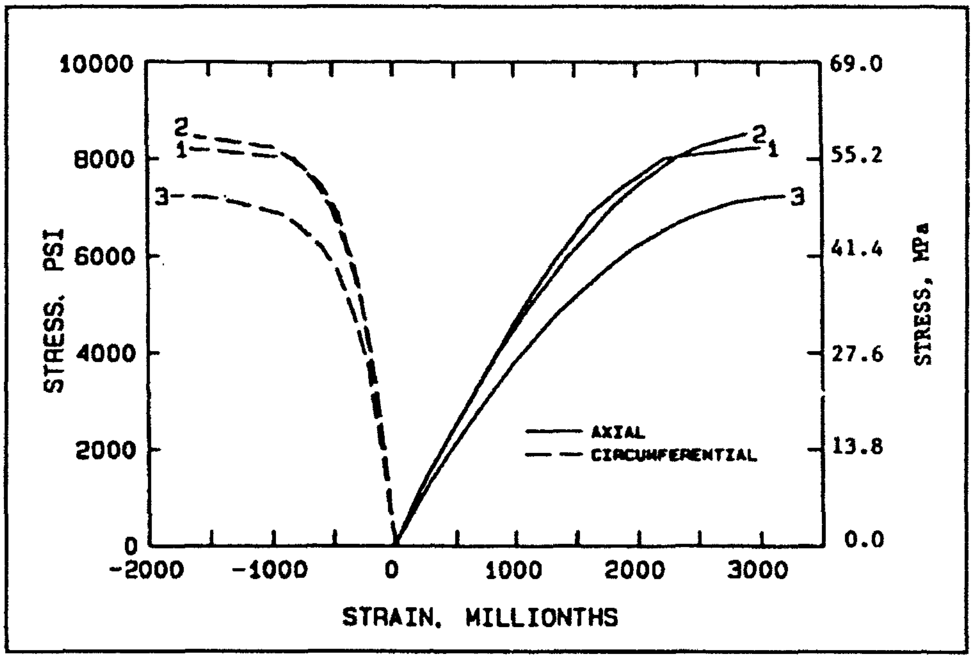

Figure 2. Stress-strain curves, compressive strength tests

Splitting Tensile Strength

The splitting tensile strength of the MSC was determined in accordance with ASTM C 496 (ASTM 1992) on three 4- by 8-in. (100- by 200-mm) cylindrical specimens. The results of these tests are tabulated in Table 4.

Table 4
Results of Splitting Tensile Tests

Specimen	Splitting Tensile Strength	
	psi	MPa
MP-4	335	2.30
MP-5	400	2.75
MP-6	310	2.15
Mean	350	2.40

Dynamic Material Properties

Pulse velocity (compressional wave; ASTM C 597 (ASTM 1992)) measurements were made nondestructively on the specimens used to determine compressive strength and splitting tensile specimens prior to destructive tests. In addition, fundamental transverse frequency and dynamic Young's modulus were determined in accordance with ASTM C 215 (ASTM 1992). Also, shear wave velocities were determined per WES laboratory techniques. The results of these measurements are given in Table 5.

Compressive Creep Tests

Compressive creep tests were conducted on two 6- by 16-in. cylindrical specimens. The test procedures were based upon the method given in ASTM C 512 (ASTM 1992) with the following exceptions.

a. Only one age of loading was considered.

b. Moisture migration to and from the specimen was assumed negligible.

c. All strains were measured using encapsulated strain gages bonded to the test specimens.

The apparatus used to perform the creep tests was a hydraulic loading frame designed to maintain a constant stress by means of a gas pressure regulator in series with a gas/oil accumulator and hydraulic ram. One control specimen was monitored to determine strains not associated with the applied loads. The creep specimens were loaded to 30 percent of the compressive strength of the MSC, determined as specified above. All data were acquired using a digital data acquisition system.

The creep test was initially planned to run for a period of 90 days. However, at approximately 45 days, the hydraulic loading system began to fail and the load was lost. Thus, only approximately 45 days of data are available.

Figure 3 shows a plot of the creep test data. As can be seen in the figure, the data plot linearly in the specific strain-time space. Specific strain is defined as strain per unit stress (ϵ/σ).

The creep behavior of MSC appears to be adequately described by the Maxwell model, a commonly studied rheological model. The most common ideal bodies used to construct a rheological model are an elastic spring and a dashpot. In the Maxwell model (Figure 4) the spring and the dashpot are in series so that they take the same load. The spring is used to represent elastic behavior, and the dashpot is used to represent viscous (time-dependent flowing behavior). This results in the total displacement of a Maxwell model being the sum of the displacements of the two elements. Rheological models imply nothing about the physical mechanisms responsible for the observed behavior

Table 5
Results of Compressional and Shear Wave Velocity Tests and Fundamental Transverse Frequency Tests

Specimen	Compressional Wave Velocity		Shear Wave Velocity		Dynamic Modulus of Elasticity		Fundamental Transverse Frequency, Hertz
	ft/s	m/s	ft/s	m/s	million psi	GPa	
MP-1	14,590	4,445	9,050	2,760	5.77	37.8	6,300
MP-2	12,470	3,800	8,700	2,650	5.76	39.9	6,280
MP-3	12,760	3,890	7,820	2,385	5.36	37.0	6,150
MP-4	14,560	4,440	8,850	2,695	5.85	40.3	6,380
MP-5	14,850	4,525	8,680	2,645	5.76	39.7	6,230
MP-6	13,860	4,225	7,910	2,410	5.52	38.1	6,200
Mean	13,850	4,220	8,500	2,590	5.67	39.1	6,260
Standard Deviation	1,010	310	510	155	0.19	1.3	80
Coefficient of Variation	7.29%		6.00%		3.35%		1.27%

of concrete but give an overall description of the phenomena of the deformation response.

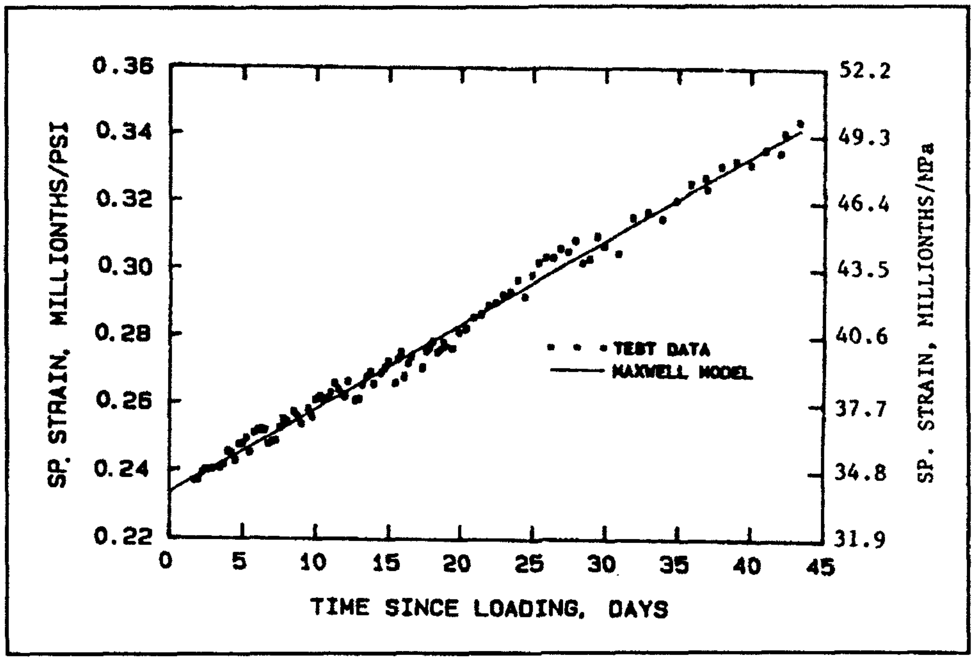

Figure 3. Results of creep test

The equation of the Maxwell model for constant stress is given as

$$\frac{\epsilon}{\sigma} = \frac{1}{\lambda}t + \frac{1}{E}$$

This equation plots as a straight line in the specific strain-time plane with 1/E the intercept and $1/\lambda$ the slope of the line. In Figure 3, a least-squares curve fitting procedure was used to determine the parameters of the Maxwell model for MSC. The values obtained were as follows:

E = 4.3×10^6 psi (29,700 MPa)

λ = 400 psi-day/millionth = 2.76 MPa-day/millionth

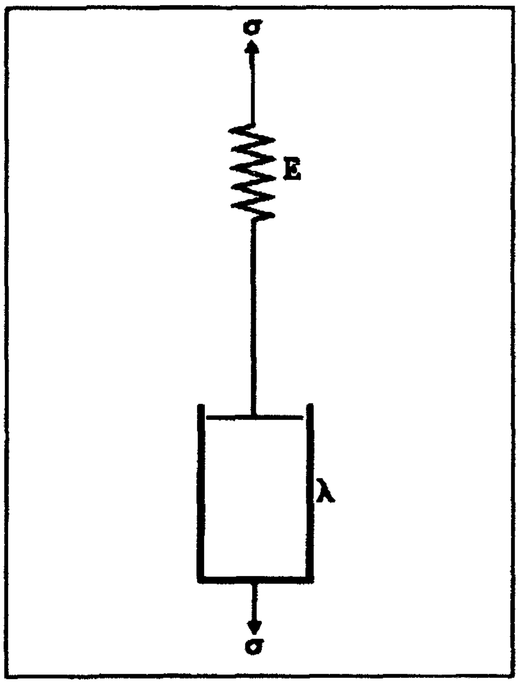

Figure 4. Schematic of Maxwell model

4 Freezing-and-Thawing Durability

Rapid Freezing-and-Thawing Durability

The resistance of the MSC to rapid freezing and thawing was determined in accordance with ASTM C 666 (ASTM 1992), Procedure A (Rapid Freezing and Thawing in Water). This testing was conducted on 12 beams, each 3½ by 4½ by 16 in. (90 by 115 by 406 mm). The results of these tests are tabulated in Table 6. These data are also shown graphically in Figures 5 and 6. Similar results were reported by Beaudoin and Sereda (1974).

Durability factors (Table 6) ranged from 4.8 to 18.0 with a mean value of 9.3. No durability factor could be determined for Beam S-8. For PCC, a durability factor of 60 after 300 cycles of freezing and thawing is considered to be a durable concrete.

The failure mode of the specimens was not that typically observed for PCC. Longitudinal or transverse cracks (or both) formed in the specimens. Some of the cracks penetrated completely through the beam causing them to break into two or more pieces. Other cracks did not completely penetrate the specimen, but reduced the integrity of the beam to the point that no flexural frequency indication could be obtained. There was no evidence of any surface deterioration.

Long-Term Freezing-and-Thawing Durability

On August 14, 1990, three 6- by 6- by 30-in. (150- by 150- by 760-mm) MSC beams were placed on the exposure rack at the WES Natural Weathering Exposure Station on Treat Island near Eastport, MN. This facility, in continuous operation since 1936, provides an opportunity to observe the performance of concrete and concrete materials exposed to a severe natural weathering environment. Specimens on the rack at the facility are exposed to an average of over 100 cycles of freezing and thawing during each winter season. The number of cycles of freezing and thawing is continuously monitored and recorded by electronic instruments. Each summer the flexural

Table 6
Results of Rapid Freezing-and-Thawing Tests

Specimen No.	Property	0 Cycles	9 Cycles	43 Cycles	79 Cycles	126 Cycles	Durability Factor
S-1	Frequency	2,100	2,075	1,400	Failed		6.6
	Rel. E, %	100	97.6	44.4			
S-2	Frequency	2,100	1,900	1,550	Failed		7.2
	Rel. E, %	100	81.9	54.5			
S-3	Frequency	2,088	2,038	1,850	1,600	Failed	15.4
	Rel. E, %	100	95.3	78.5	58.7		
S-4	Frequency	2,088	2,050	1,100	Failed		5.4
	Rel. E, %	100	96.4	27.8			
S-5	Frequency	2,075	2,025	1,100	Failed		5.4
	Rel. E, %	100	95.2	28.1			
S-6	Frequency	2,100	1,938	1,100	Failed		4.8
	Rel. E, %	100	85.2	27.4			
S-7	Frequency	2,088	1,988	1,450	Failed		6.8
	Rel. E, %	100	90.7	48.2			
S-8	Frequency	2,075	2,000	Failed			---
	Rel. E, %	100	92.9				
S-9	Frequency	2,125	2,075	1,700	1,275	Failed	9.6
	Rel. E, %	100	95.3	64.0	36.0		
S-10	Frequency	2,063	2,025	1,875	1,650	1,400	18.0
	Rel. E, %	100	96.3	82.6	64.0	46.1	
S-11	Frequency	2,063	1,950	1,750	1,550	Failed	14.4
	Rel. E, %	100	89.3	74.3	56.5		
S-12	Frequency	2,050	1,925	1,575	Failed		8.4
	Rel. E, %	100	88.2	59.0			

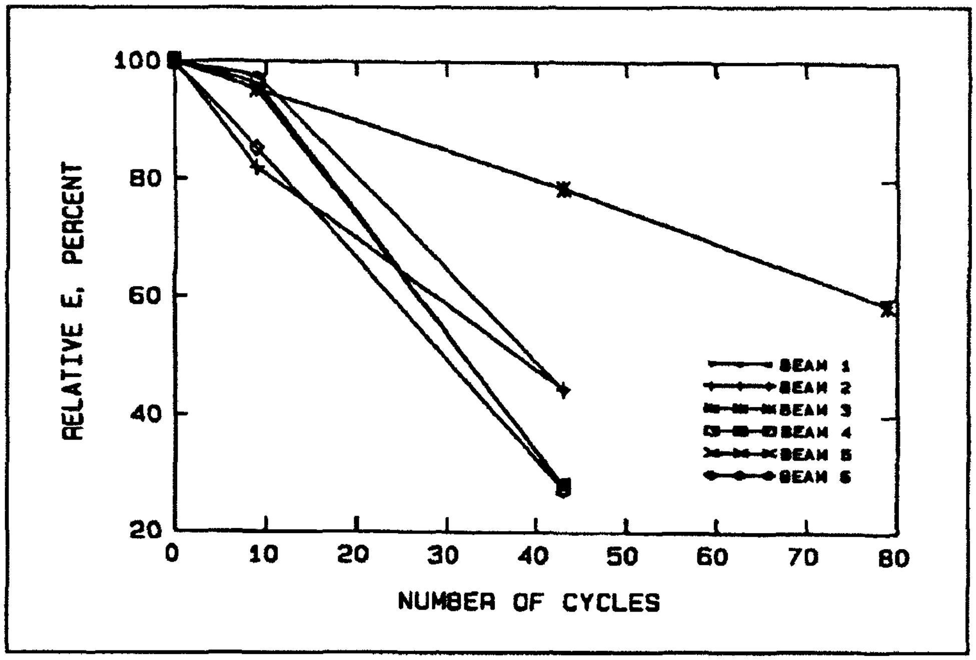

Figure 5. Dynamic Young's modulus versus number of freezing-and-thawing cycles, Beams 1 through 6

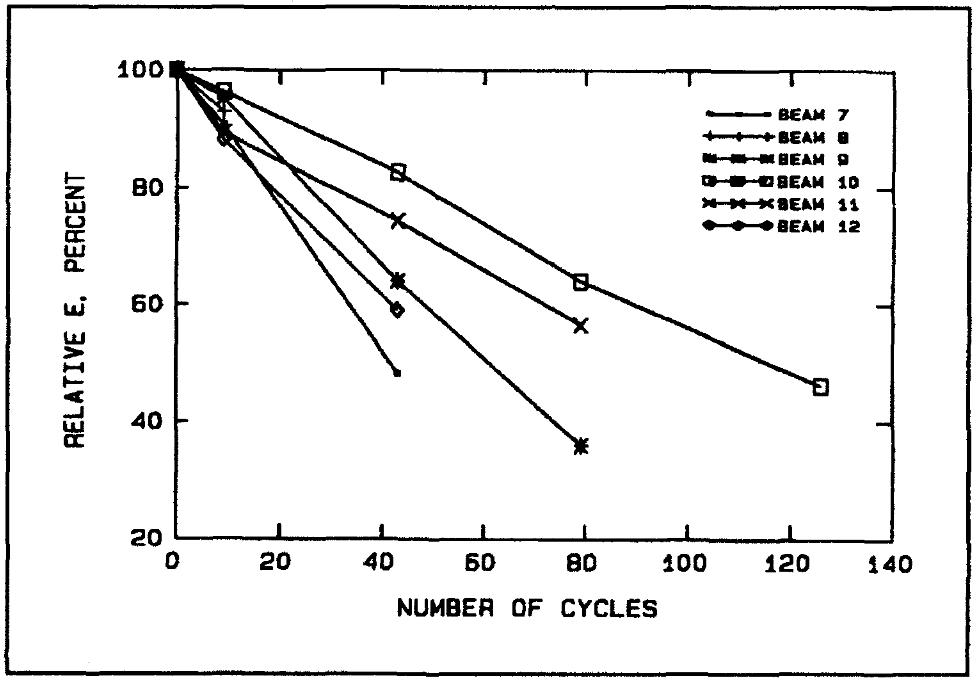

Figure 6. Dynamic Young's modulus versus number of freezing-and-thawing cycles, Beams 7 through 12

frequencies of the specimens are determined (ASTM C 215 (ASTM 1992)) and recorded along with the number of cycles of freezing and thawing. The specimens are also photographed annually. An inspection of the facility is conducted by WES biennially, and a data report is available to document the observed data.

At the end of the first winter of exposure on the rack at Treat Island, the results of the natural weathering tests were similar to the results obtained in the laboratory. After 75 cycles of freezing and thawing, the relative modulus of elasticity averaged 54 percent of its original value. Surface cracks were observed on all three specimens.

5 Bond Tests

General

MSC can potentially be used as a repair material for existing PCC structures or pavements. However, to be effective as a repair material, a good bond must be formed between the MSC and the existing PCC. A limited number of tests were performed to determine the bond strength between MSC and PCC. In addition, two commercially available epoxy bonding agents were used to determine if the bond could be enhanced. The results of these tests are reported below.

Test Description

Bond tests were conducted to determine the bond strength between hardened PCC and MSC placed against it. These tests were conducted in accordance with ASTM C 882 (ASTM 1992).

Seven 6- by 12-in. (150- by 300-mm) cylindrical concrete specimens were selected from the laboratory from a completed testing program. These cylinders were saw cut into two pieces along a diagonal line as specified in ASTM C 882. The cut faces of the cylinders were sandblasted to form a uniform surface. The 14 half-cylinders were subsequently placed in steel cylinder molds in preparation for filling the molds with MSC.

Five of the cylinders were cast with MSC placed directly against PCC surface. The remaining cylinders were coated with one of two commercially available epoxy-based bonding agents just prior to placement of the molten MSC. Both bonding agents (referred to in this report as Product S and Product C) were two-component structural adhesives suitable for bonding fresh, plastic PCC to hardened PCC. Product C is a high-viscosity product at room temperature; Product S is a medium viscosity product at room temperature.

The components of the two adhesive compounds were mixed according to the manufacturer's instructions. The adhesive compounds were then applied to the PCC specimens and allowed to become tacky (approximately 55 min).

The MSC was placed directly against the adhesive compounds in the steel cylinder molds.

All bond strength specimens were tested in universal testing machine and the maximum loads and failure modes were recorded. If the specimen failed along the bond plane, the maximum load was divided by the area of the bond plane (ASTM C 882 (ASTM 1992) to determine the bond strength. If the bond held beyond crushing failure of the specimen, the compressive strength was calculated using the cross-sectional area of the cylinder.

Test Results

The test results are summarized in Table 7. For all specimens cast without a bonding agent, the failure was along the bond plane with a mean bond strength of 2,035 psi (14.0 MPa). For all cylinders cast using Product S as a bonding agent, the failure was also along the bond plane. However, the mean bond strength was reduced to 1,740 psi (12.0 MPa), indicating that the quality of the bond was reduced by Product S. However, the specimens cast using Product C (with the exception of one specimen) all failed in compression prior to bond failure at the compressive strength of the PCC. The one specimen which failed along the bond plane exhibited a bond strength of 2,970 psi (20.5 MPa). Thus, it appears that bond can be obtained between MSC cast onto PCC without the use of bonding agents. However, more research is required to determine the effects of bonding agents on the bond between MSC and PCC. The results of this test program have demonstrated that the bond can be enhanced or inhibited by different commercially available bonding agents.

Table 7
Results of Bond Tests, MSC to PCC

Specimen	Bonding Agent	Type of Failure	Bond Strength		Compressive Strength	
			psi	MPa	psi	MPa
BP-1	None	Bond	2,040	14.1		
BP-2	None	Bond	2,185	15.1		
BP-3	None	Bond	2,120	14.6		
BP-4	None	Bond	2,025	14.0		
BP-5	None	Bond	1,680	11.6		
BP-6	None	Bond	2,155	14.9		
	Mean Bond Strength		2,035	14.0		
BS-1	Product S	Bond	1,980	13.7		
BS-2	Product S	Bond	1,840	12.7		
BS-3	Product S	Bond	1,735	12.0		
BS-4	Product S	Bond	1,415	9.8		
	Mean Bond Strength		1,740	12.0		
BC-1	Product C	Compressive			2,210	15.2
BC-2	Product C	Compressive			2,545	17.6
BC-3	Product C	Compressive			2,756	19.0
BC-4	Product C	Bond	2,970	20.5		

6 Beam Tests

Beam Design

Beam tests were conducted to observe the behavior of plain and reinforced MSC beams during loading. The objective of these tests was to verify that the basic assumptions of limit states design for reinforced PCC beams were valid including the strain distribution across the cross section of the beam and the development of an effective moment-resisting couple.

Two beams each of three configurations were to be tested: two plain (unreinforced) beams (denoted Beams P1 and P2), two beams with flexural reinforcement only (denoted Beams R1 and R2), and two beams with flexural and shear reinforcement (denoted Beams RS1 and RS2). The reinforcement details were designed in accordance with American Concrete Institute (ACI) 318 (ACI 1992) requirements with the exception of the required development length of the flexural steel. This requirement could not be met because of restrictions imposed by the dimensions of the beam. The overall dimensions of the beams were determined by a set of preexisting steel molds at WES used for casting tensile strain capacity beams for mass PCC. These molds were 12 by 12 in. (300 by 300 mm) in cross section and 66 in. (1,680 mm) in length. The Corps' method (CRD-C 71 (USAEWES 1949)) for tensile strain capacity calls for third-point loading on a 60-in. (1525-mm) span. It was determined early in the program to use this configuration for direct comparison with tensile strain capacity tests on PCC mixtures with comparable compressive strength.

The material properties assumed for the beam design were as follows:

f'_c = 7,000 psi (48.3 MPa)
f_y = 60,000 psi (414 MPa)

The cover was selected in accordance with ACI 318 requirements for precast beams. Three each No. 9 bars were selected for the flexural reinforcement, and No. 3 shear stirrups spaced at 1¾ in. (44.5 mm) were placed in the region between the supports and load points on each end. Table 8 summarizes the beam design. Figure 7 shows an elevation of the beam, and Figure 8 shows a transverse cross section. The details of the shear stirrup design are shown in Figure 9.

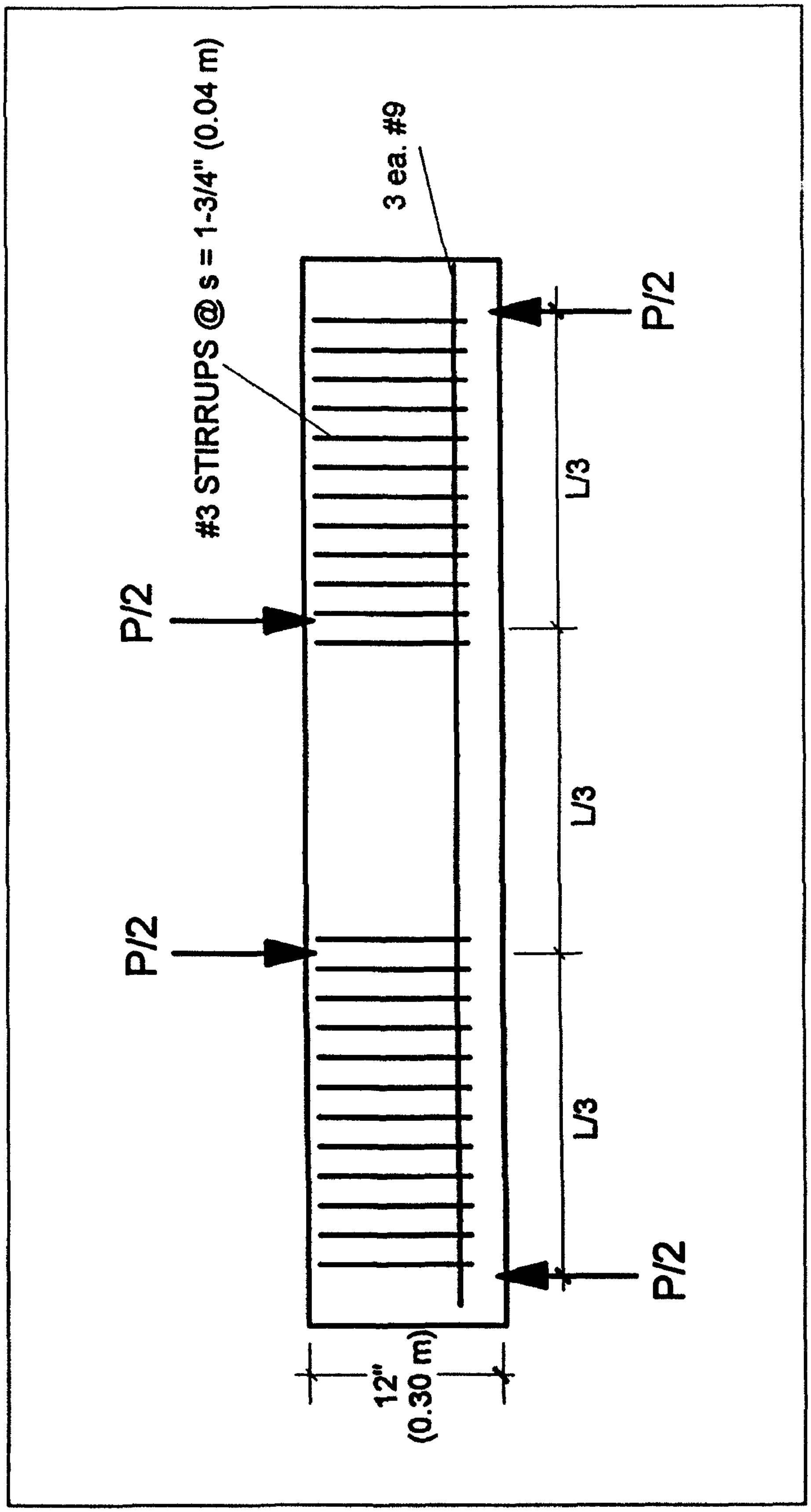

Figure 7. Elevation of fully reinforced beam

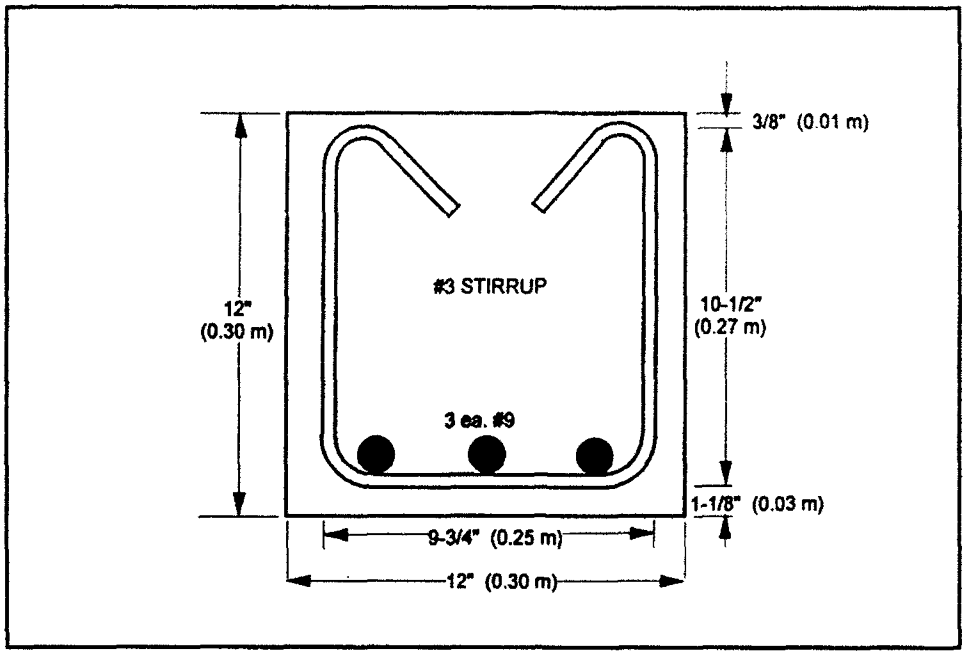

Figure 8. Cross section of beam

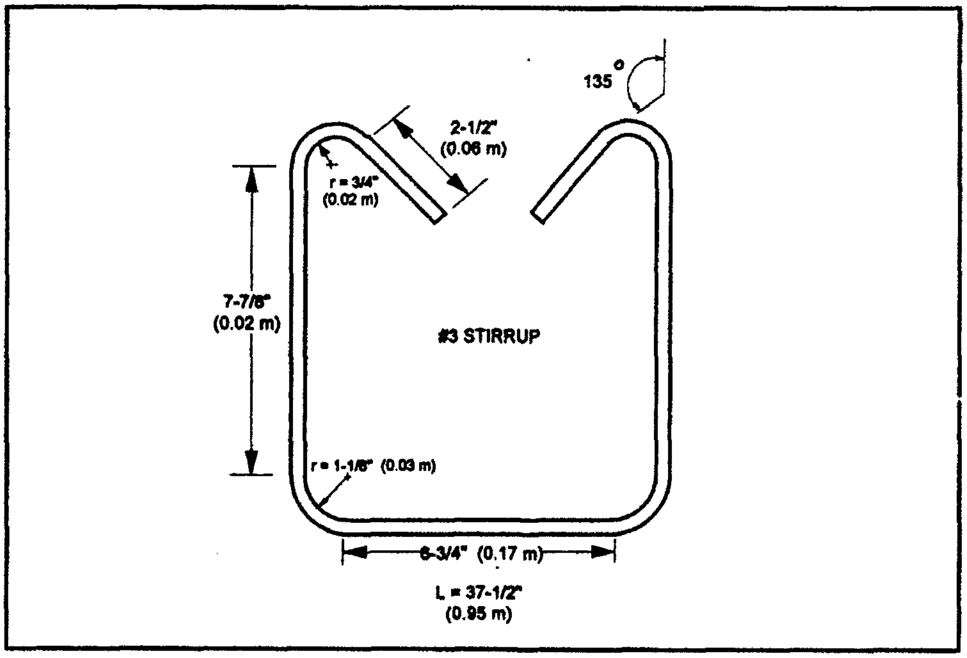

Figure 9. Shear stirrup detail

Table 8 Beam Design Summary	
ACI 318 (ACI 1992a) Parameter	Value
Beam width, b	12 in. (300 mm)
Effective depth, d	9.82 in. (250 mm)
Area of flexural steel, A_s	3.00 in.^{2} (1,935 mm^2)
Reinforcement ratio, ρ	0.0255
Area of shear steel, A_v	0.44 in.^{2} (280 mm^2)
Ultimate moment capacity, M_u	1,540 kip-in. (174 KN-m)

Instrumentation Details

To study the distribution of strains across the depth of the beam, an array of strain gages were required at various locations through its depth. Gages were required to be placed both on the external surfaces of the beam, on reinforcing bars, and embedded at selected locations in the concrete. The instrumentation plans for the beam tests are shown in Figures 10, 11, and 12.

No commercially available embedable strain gages could be located capable of surviving the placement temperatures of MSC. Thus, an embedable strain gage was developed at WES for this purpose. The gage consisted of a 0.25-in.-diameter (6-mm) deformed steel bar 4 in. (100 mm) in length. The cross-sectional area of the central 1-in. (25 mm) section was machined to form a smooth surface for application of a strain gage. On each end of the bar, 1-in.-diameter (25-mm) steel discs (approximately ¼ in. (6 mm) thick) were welded to form a barbell-shaped gage body. A strain gage, temperature-resistant to 500 °F (260 °C), was bonded to the gage body, and teflon-coated instrumentation wire was used to complete the leads for attachment to the data acquisition system. A heavy-duty gage coating compound was applied to the gages for additional protection. Several prototype gages were manufactured and cast into 3- by 6-in. (75- by 150-mm) cylinders of sulfur capping compound (cast at 300 °F (149 °C)). These cylinders were allowed to cool and were tested in compression to verify the accuracy and reliability of the gages. Excellent results were obtained, and this design was used to manufacture all embedded strain gages (not attached to a reinforcing bar). These gages are denoted by the initials "CE" in the gage designation.

At locations where flexural reinforcing bars were available, thermally resistant strain gages were placed on the reinforcing bars. At the location of the gage, the bars deformations were removed, and the procedure described above was used to bond and protect the gages. All gages placed on flexural steel bars are denoted by the initials "SM" in the gage designation.

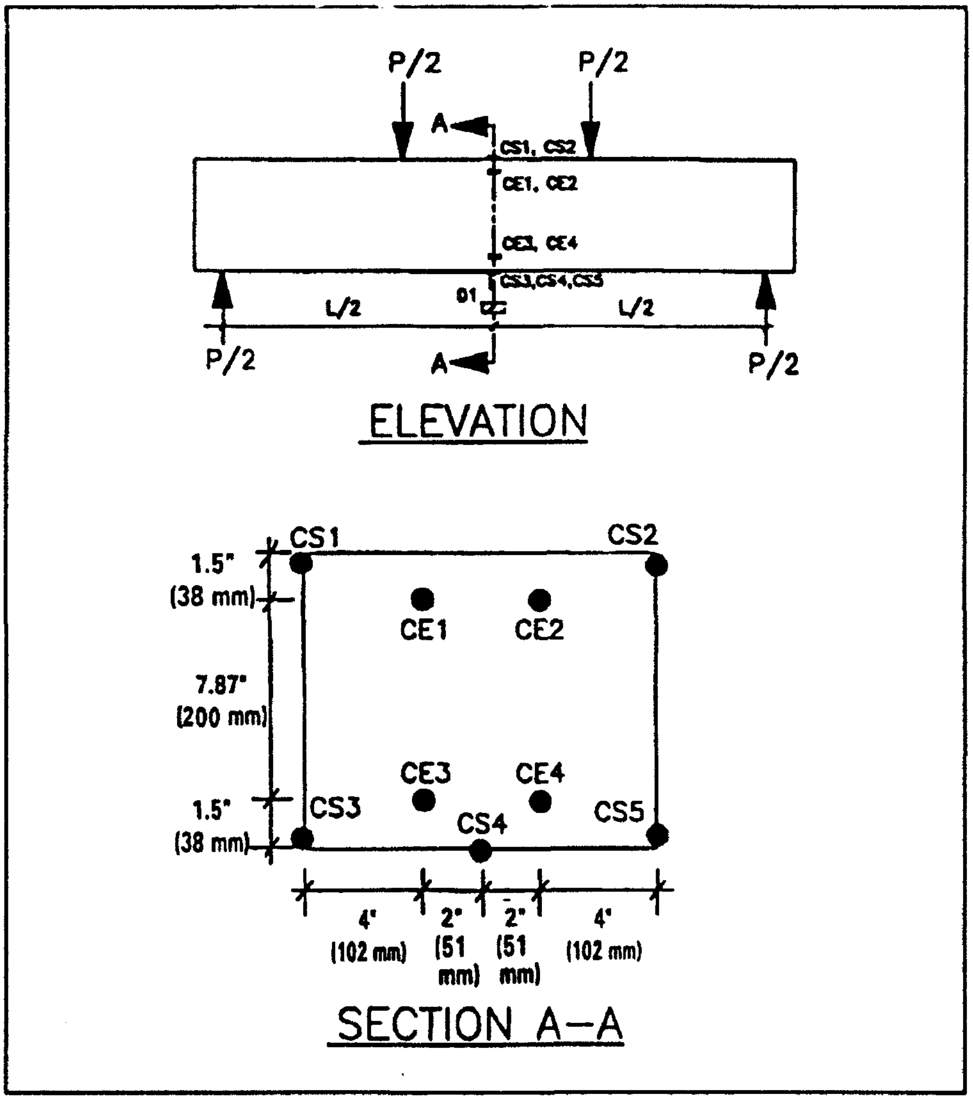

Figure 10. Instrumentation plan, unreinforced beams

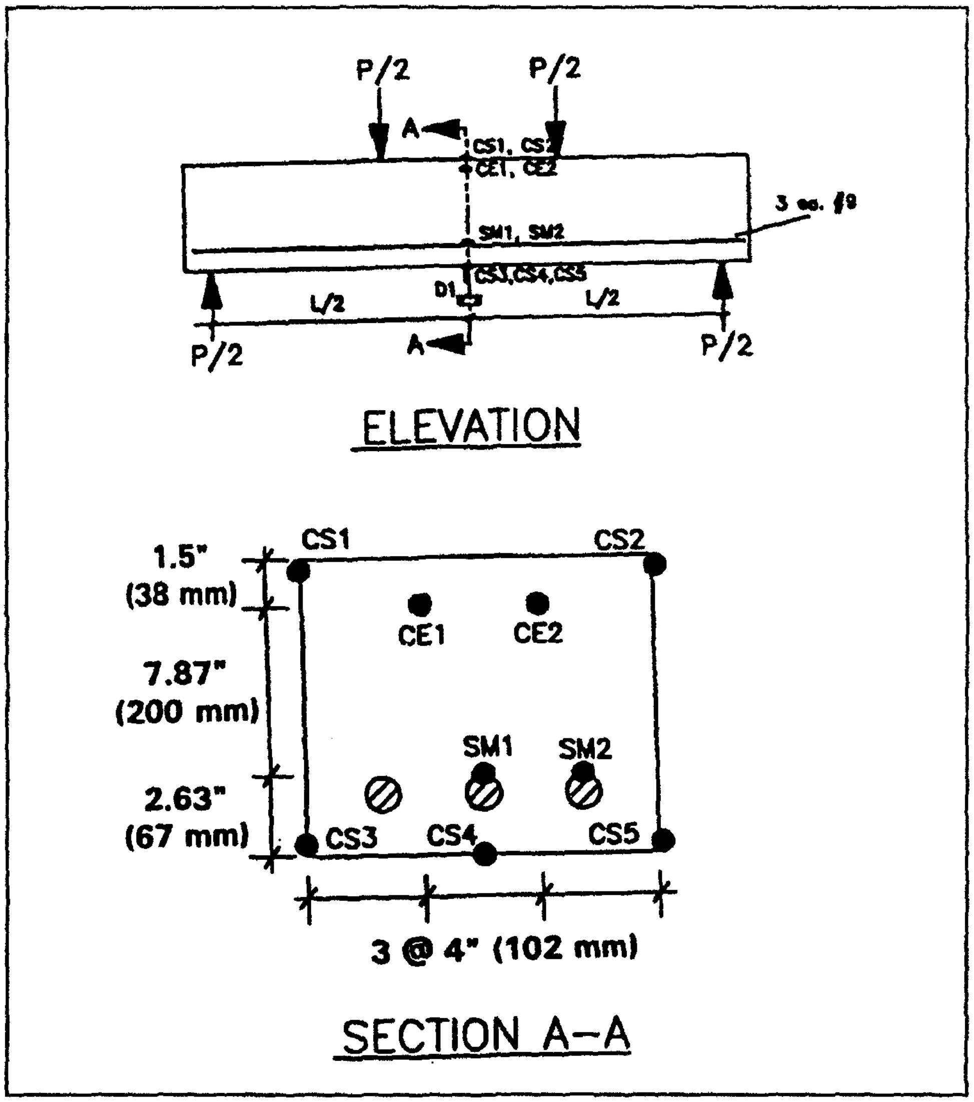

Figure 11. Instrumentation plan, beams with flexural steel only

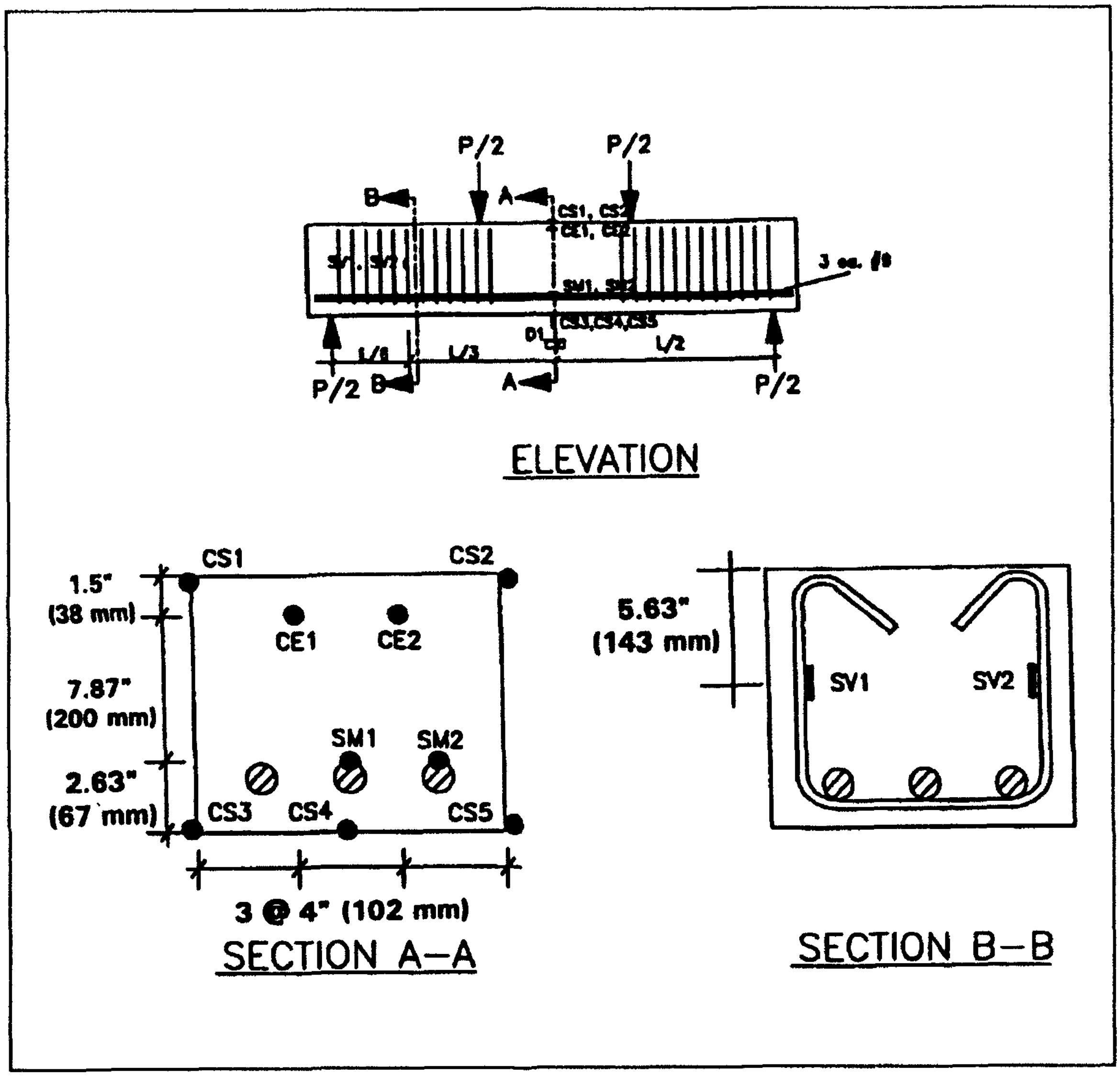

Figure 12. Instrumentation plan, fully reinforced beam

Gages were also applied to a shear stirrup in both of the fully reinforced beams. The same application procedure was followed. All gages on shear stirrups are denoted by the initials "SV."

The beam's center line deflection was recorded during each test, and is denoted as "D1."

Test Procedures

A load-spreader beam system was used to load the beams at the third points. The load was provided by a 300-kip (1,334-KN) capacity hydraulic actuator controlled by a servo system. The load rate was set at 3,600 lb/min (16 KN/min). An electronic load cell between the hydraulic actuator and the load-spreader beam measured the applied load. All data (including applied load, displacement, and strains) were acquired in real time with a digital data acquisition system. A photograph of the testing system is shown in Figure 13.

Figure 13. Photograph of beam test system

Test Results

Beams P1 and P2

All strain gages on the tension side of Beam P1 failed to produce data. The embedded gages on the tension side (gages CE3 and CE4) were destroyed during the casting operation, and the surface gages (CS3, CS4, and CS5) debonded due to improper bond to the MSC. This problem was corrected, however, in subsequent tests. The data plots of all gages are shown in Appendix A.

Beam P1 failed at an applied load of 27,900 lbf (124 KN) resulting in a bending moment at failure of 279 kip-in. (31.5 KN-m). Failure occurred at the center line of the beam (Figure 14). The maximum fiber stress (ASTM C 78 (ASTM 1992)) modulus of rupture was 970 psi (6.69 MPa). A posttest photograph of Beam P2 is shown in Figure 15. Figure 16 shows the strain distribution across the depth of the beam just prior to failure. From the figure it is apparent that the maximum tensile strain (assuming a linear strain distribution) was approximately 200 millionths. Using the CRD-C 71 (USAEWES 1949) definition of tensile strain capacity (maximum tensile strain at 90 percent of ultimate load), the tensile strain capacity was calculated as 180 millionths. Values ranging from 117 to 142 millionths were reported by Bombich and Magoun (1982) for a 7,350-psi (50.7-MPa) PCC.

Prior to testing Beam P2, a preexisting vertical crack was noted near the center line of the beam. Upon loading, the beam failed at the crack at a load of only 600 lbf (2.7 KN). Thus, no useful data were obtained.

Beams R1 and R2

The failure mode for Beam R1, as expected, was shear failure. However, the beam failed prematurely due to inadequate reinforcing details over the supports. The maximum load during the test was 75,000 lbf (334 KN), and the maximum bending moment was 750 kip-in. (84.7 KN-m). First flexural cracking occurred near the center line of the beam at a load of 31,000 lbf (138 KN), which agrees reasonably well with the ultimate load of Beam P1. Inadequate embedment was provided beyond the support due to (a) deficient development length of the flexural steel beyond the supports and (b) improper centering of the reinforcing bars in the beam prior to casting. These flaws caused the one end of the beam to separate violently at failure along the shear crack. After this test was conducted, it was determined that in all subsequent tests, the span would be reduced to 56 in. (1.42 m), reducing the distance between loading points proportionally to maintain third-point loading.

The displacement and strain data from Beam R1 are given in Appendix B. The strain data were used to construct the strain-distribution diagram shown in Figure 17. Figure 18 shows a posttest photograph of the beam.

A posttest photograph of Beam R2 is shown in Figure 19. This beam also failed in shear. First flexural cracking occurred near the center line at a load of 31,000 lbf (138 KN), and failure occurred at a load of 135,000 lbf (601 KN) or a bending moment of 1,215 kip-in (137 KN-m). The span for this beam was 56 in. (1.42 m).

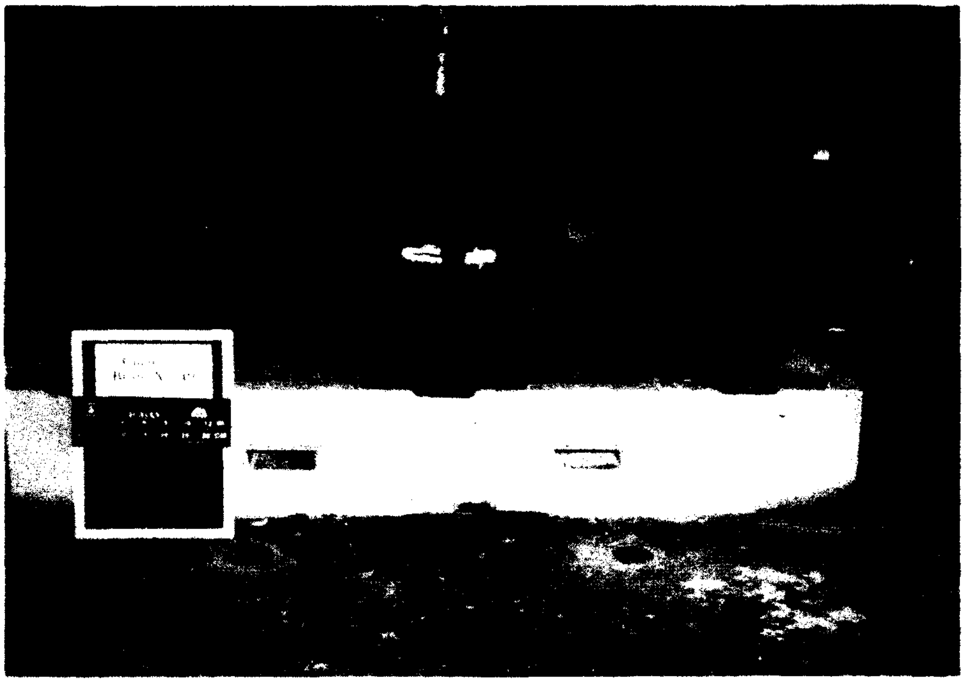

Figure 14. Posttest photograph, Beam P1

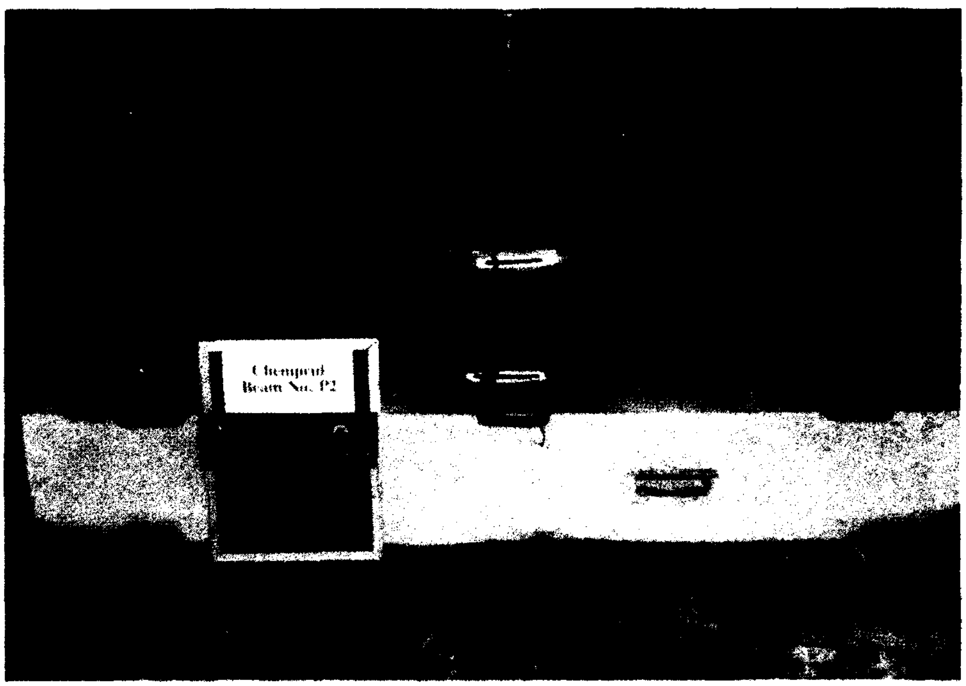

Figure 15. Posttest photograph, Beam P2

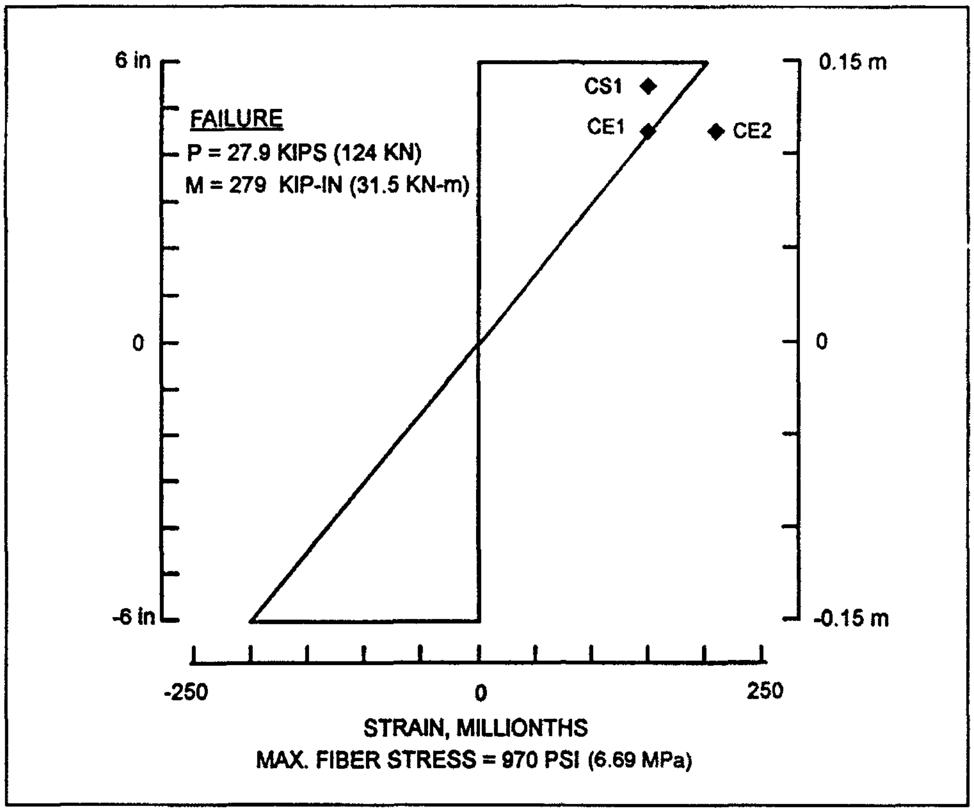

Figure 16. Strain distribution, Beam P1

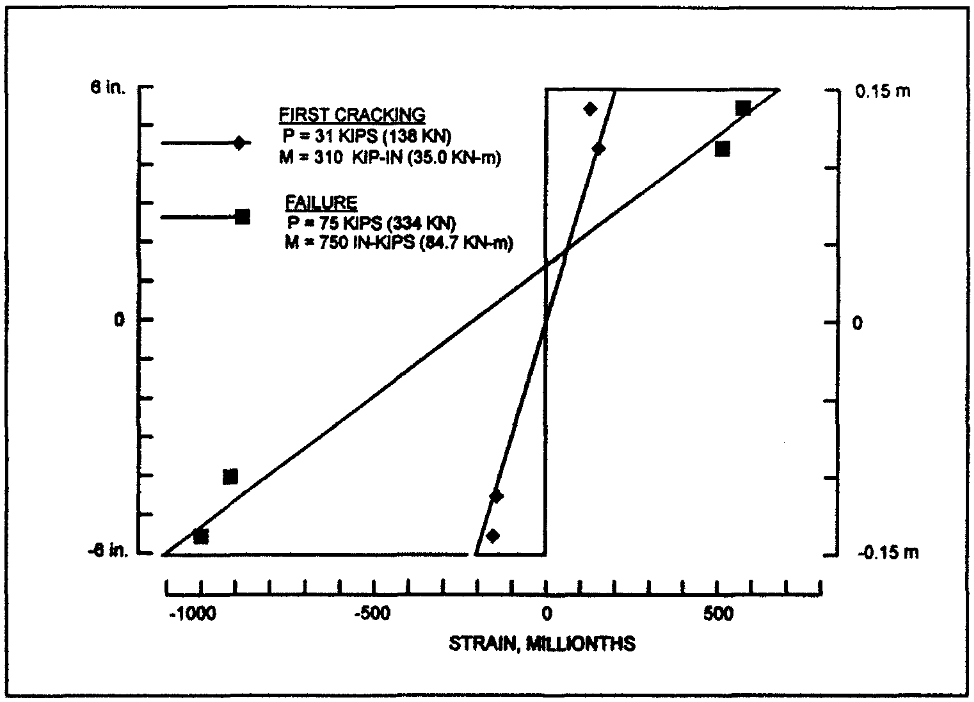

Figure 17. Strain distribution, Beam R1

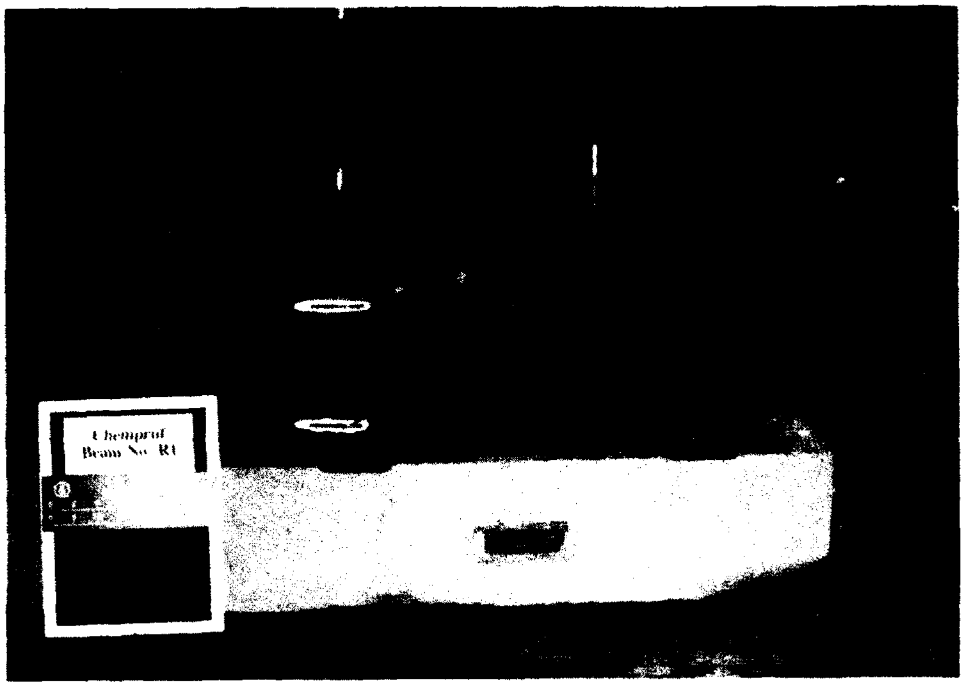

Figure 18. Posttest photograph, Beam R1

Figure 19. Posttest photograph, Beam R2

The shear crack which lead to failure of the specimen propagated from the region of the right support along the flexural reinforcement for a distance of approximately 10 in.(0.25 m), and then it turned sharply upward and to the left to just under the right load point.

Displacement and strain data for Beam R2 are contained in Appendix C. The strain data were used to draw the strain-distribution diagram shown in Figure 20. This diagram shows that the flexural reinforcement was strained to approximately 1,500 millionths just prior to failure. This strain level, as well as the strain histories of gages SM1 and SM2 (Appendix C), indicates the yielding of the flexural steel had not occurred at failure.

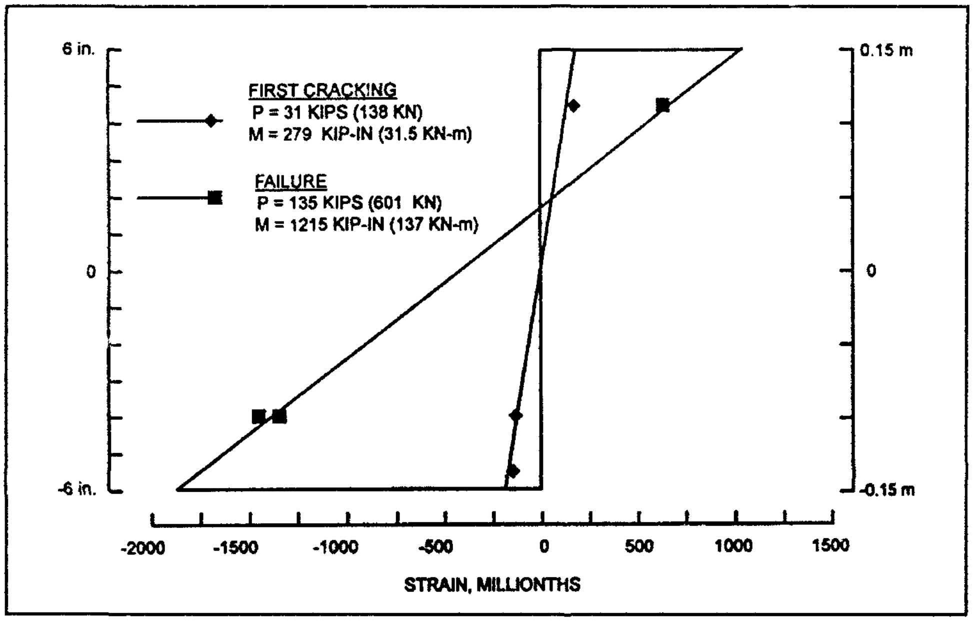

Figure 20. Strain distribution, Beam R2

Beams RS1 and RS2

Posttest photographs of beams RS1 and RS2 are shown in Figures 21 and 22, respectively. Beam RS1 experienced first flexural cracking at a load of 31,000 lbf (138 KN), shear cracking occurred at 135,000 lbf (601 KN), and failure occurred at 196,000 lbf (872 KN). With the 56-in. (1.42-m) span, the ultimate bending moment was 1,764 kip-in (199 KN-m). The failure mode was characterized by multiple shear cracks extending from the region of the support to the point of application of the load. Considerable spalling of the concrete on the exterior of the shear stirrups was noted.

Data from the test are presented in Appendix D. A diagram showing the distribution of strains through the depth of the section is shown in Figure 23.

Figure 21. Posttest photograph, Beam RS1

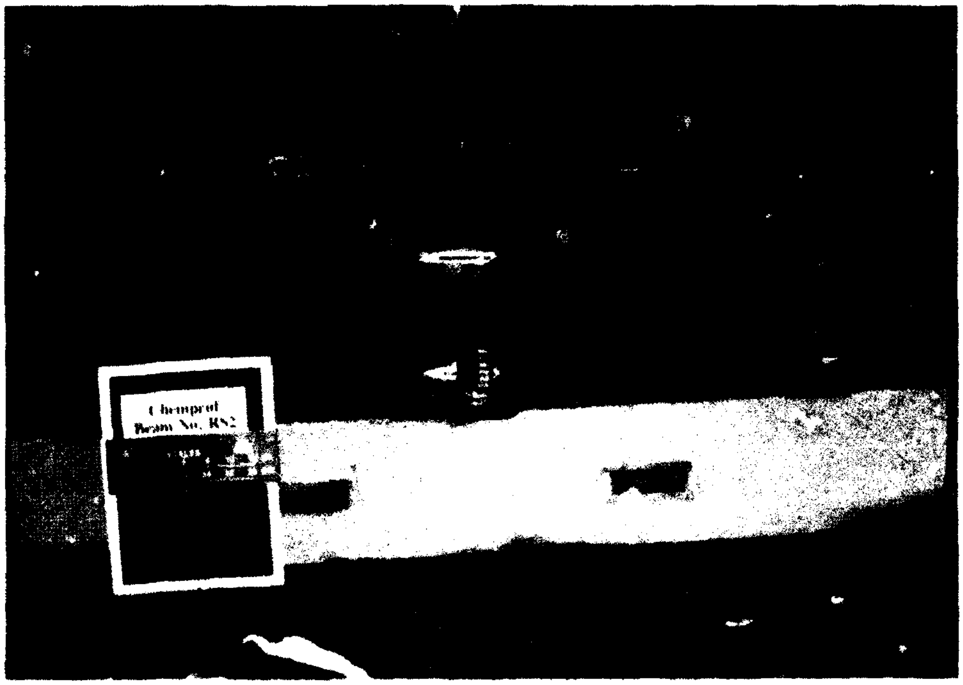

Figure 22. Posttest photograph, Beam RS2

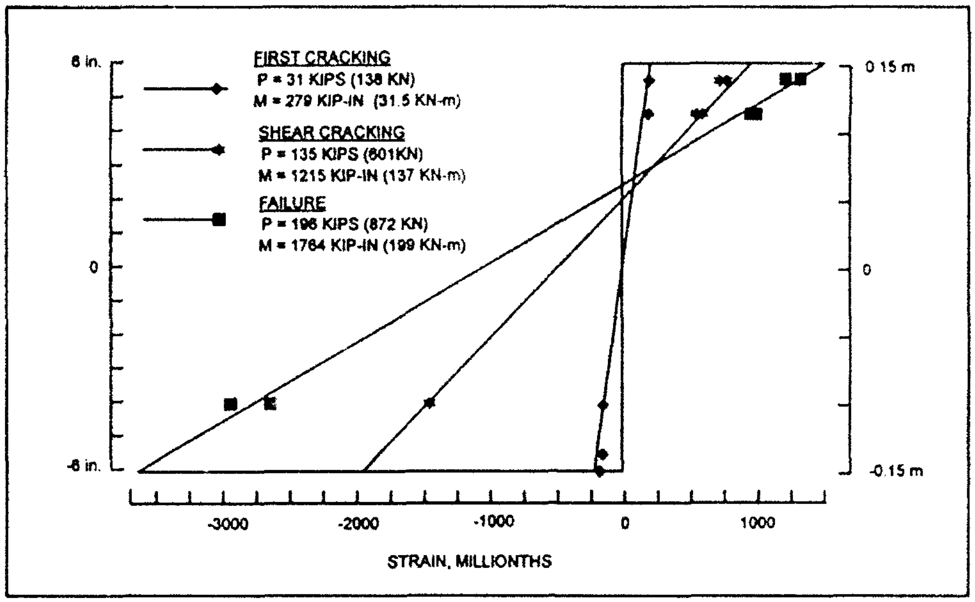

Figure 23. Strain distribution, Beam RS1

Beam RS2 failed at a load of only 118,000 lbf (525 KN), considerably less than Beam RS1. Although Beam RS2 contained shear reinforcement, it experienced premature failure for the same reasons as Beam R1. A strain distribution diagram is shown in Figure 24. Data from the tests are presented in Appendix E.

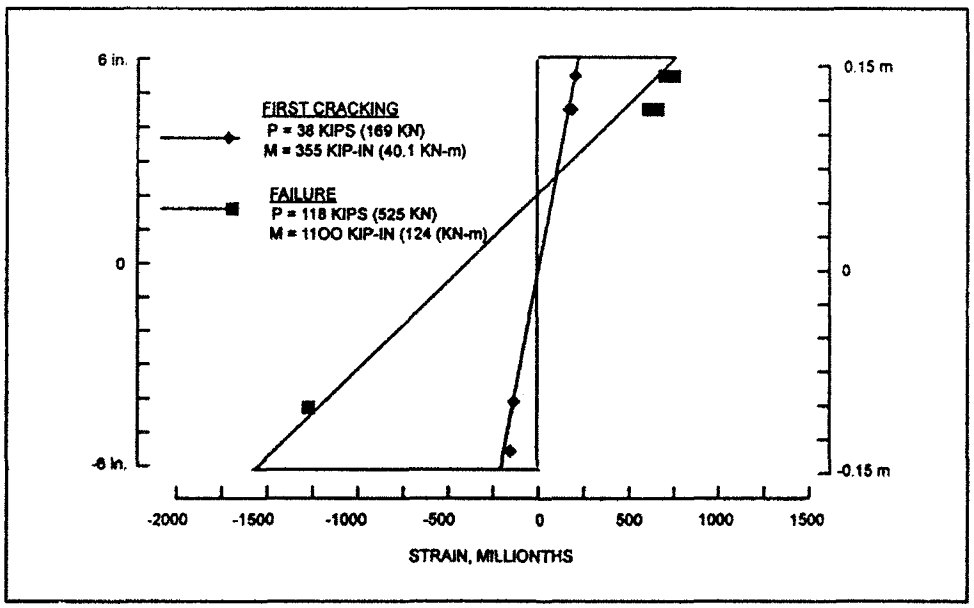

Figure 24. Strain distribution, Beam RS2

7 Conclusions and Recommendations

Conclusions

From the tests conducted under this program, the following conclusions can be drawn:

a. In uniaxial compression, MSC behaves similarly to a PCC with a comparable compressive strength. The modulus of elasticity and Poisson's ratio of MSC are comparable in magnitude to that of a PCC of comparable strength. It appears that the ACI 318 (ACI 1992a) equation for modulus of elasticity for normal weight concrete as a function of compressive strength is valid for MSC.

b. The compression and shear wave velocities, flexural frequency, and dynamic Young's modulus for MSC are comparable to that of a PCC with comparable compressive strength.

c. The splitting tensile strength of MSC is approximately 4½ percent of the compressive strength.

d. The tensile strain capacity and modulus of rupture of MSC is comparable to, if not slightly greater than, that expected for a PCC with a comparable compressive strength.

e. Rapid freezing-and-thawing durability tests have indicated that freezing-and-thawing durability of MSC is below that of air-entrained PCC. Similar results were obtained from natural weathering freezing-and-thawing tests at the Treat Island, Maine, Natural Weathering Exposure facility.

f. For MSC cast against carefully prepared PCC specimens, bond strengths of over 2,000 psi (13.8 MPa) were obtained without the use of any bonding agents. Additional tests conducted on specimens in which two commercially available, epoxy-based, structural adhesives were applied to the PCC immediately prior to placing the MSC indicated that bonding may be either enhanced or diminished by the use of bonding agents.

g. Six beam tests were conducted: two unreinforced beams, two with flexural reinforcement only, and two fully reinforced beams. Three of the six tests experienced premature failure: one plain beam (P2) failed due to a preexisting crack; one beam (R1) failed due to flexural reinforcement only; and one beam (RS2) with flexural and shear reinforcement failed prematurely due to inadequate reinforcement detailing over the supports.

h. The remaining three beams provided information indicating that MSC conforms to the basic assumptions of reinforced concrete beam design including the formation of an effective moment-resisting couple. The ductility of MSC in the post-yield regime, however, has not been determined in these tests.

Recommendations

MSC is recommended for consideration for use in structural elements in locations where the concrete is subjected to aggressive chemical attack. However, until the freezing-and-thawing durability of MSC is improved, it is not recommended for use in environments where it will be subjected to freezing and thawing.

MSC must be placed and finished at elevated temperatures. Therefore, it is recommended that forms be preheated and possibly insulated to prevent rapid loss of workability. Moving air will tend to cause the surface of the concrete element to cool rapidly and thus impede obtaining a smooth surface finish. Therefore, it is recommended that wind or air currents be blocked in the vicinity of the forms. Inherit problems in placing and finishing MSC can be mitigated by precasting structural elements at a location where temperature and air currents can be more readily controlled.

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c. Designation C 78-84. "Standard test method for flexural strength of concrete (Using simple beam with third-point loading)."

d. Designation C 215-85. "Standard test method for fundamental transverse, longitudinal, and torsional frequencies of concrete specimens."

e. Designation C 469-83. "Standard test method for static modulus of elasticity and poisson's ratio of concrete in compression."

f. Designation C 496-88. "Standard test method for splitting tensile strength of cylindrical concrete specimens."

g. Designation C 512-82. "Standard test method for creep of concrete in compression."

h. Designation C 597-832. "Standard tests method for pulse velocity through concrete."

i. Designation C 666-84. "Standard test method for resistance of concrete to rapid freezing and thawing."

j. Designation C 882-87. "Standard test method for bond strength of epoxy-resin systems used with concrete."

Beaudoin, J. J., and Sereda, P. J. (1974). "Freeze-thaw durability of sulfur concrete," Division of Building Research, National Research Council, Ottawa, Canada.

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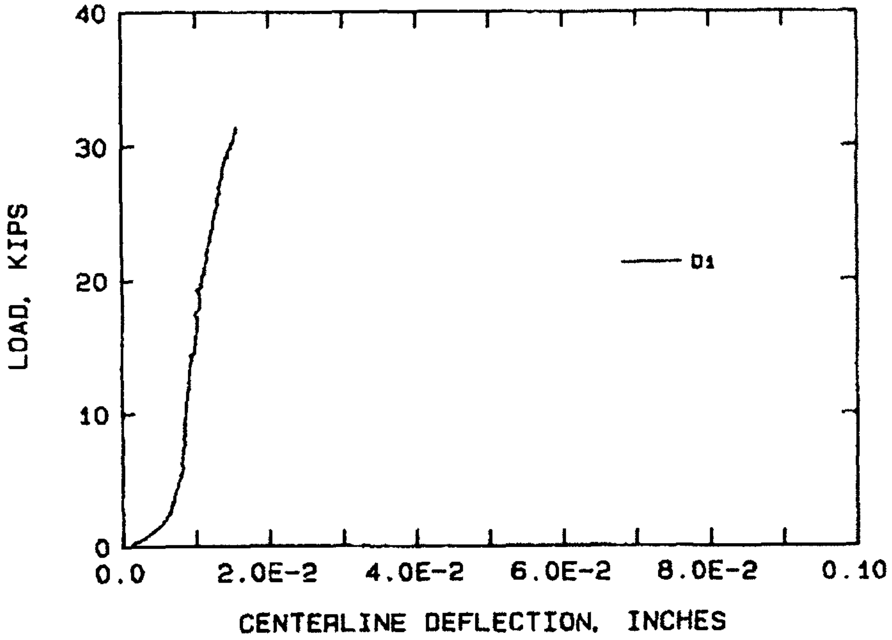
U.S. Army Engineer Waterways Experiment Station. (1949). *Handbook for concrete and cement* (with quarterly supplements), Designation CRD-C 71, "Standard test method for ultimate tensile strain capacity of concrete," Vicksburg, MS.

Appendix A
Data Plots, Beam P1



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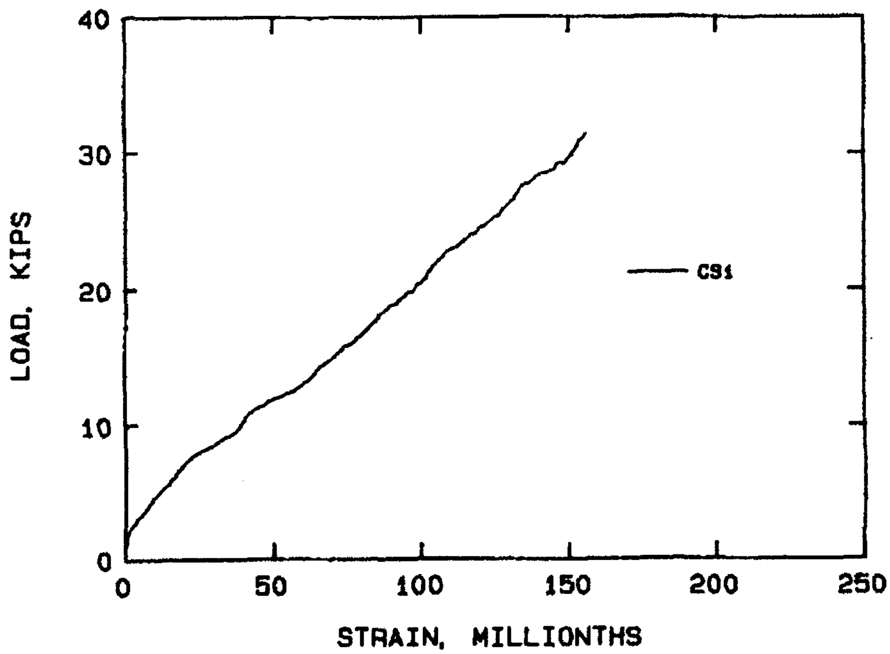


Figure A2

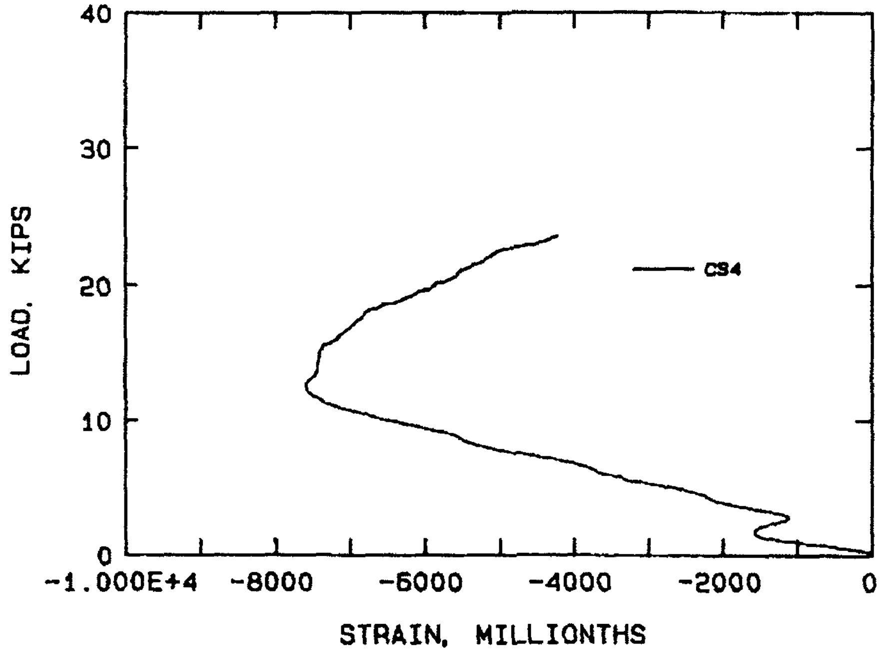


Figure A3

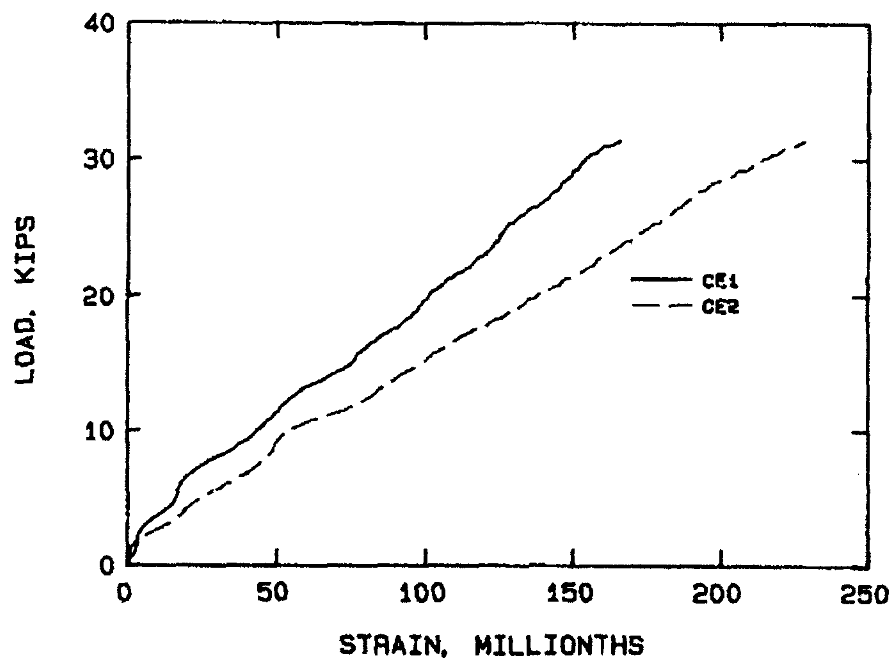
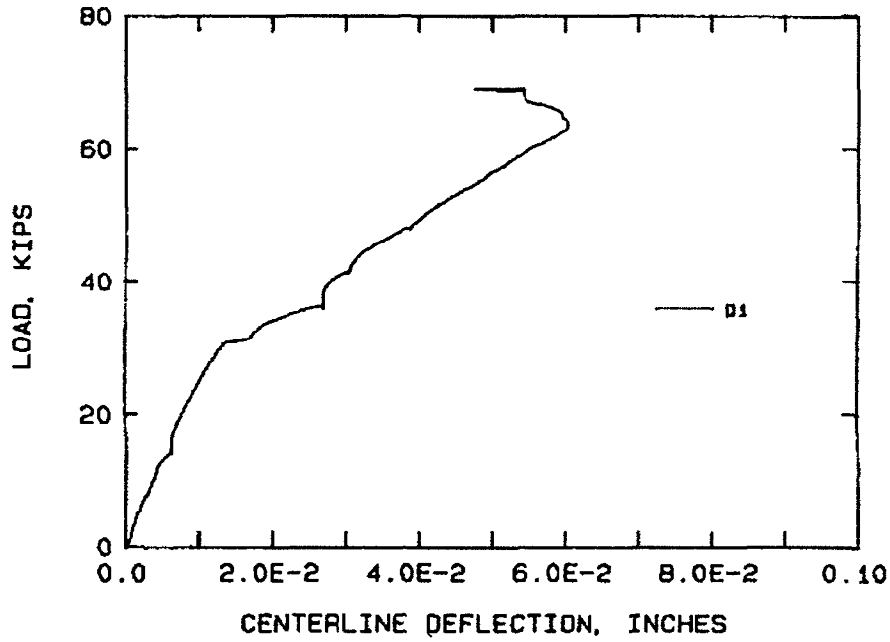


Figure A4

Appendix B
Data Plots, Beam R1



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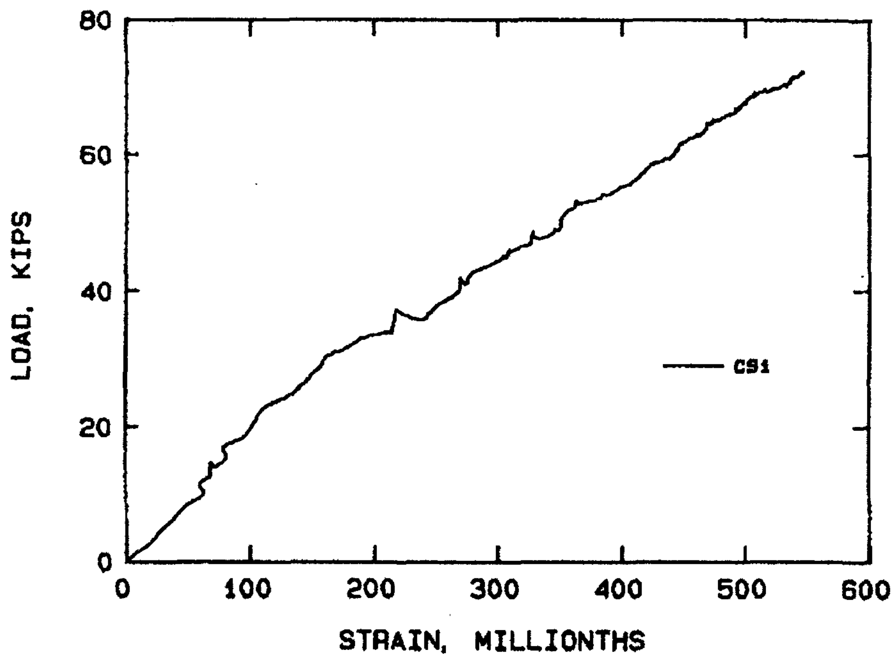

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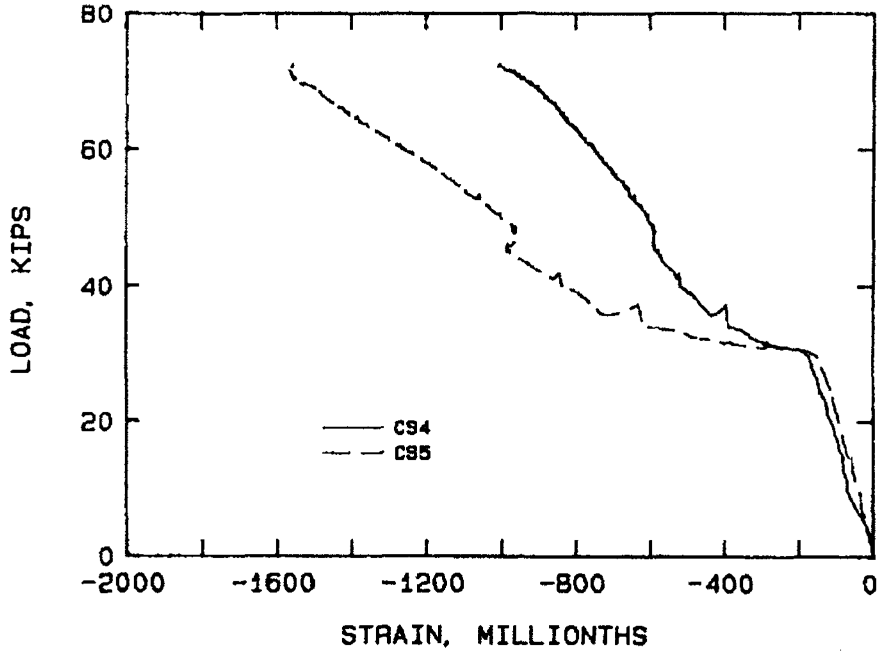

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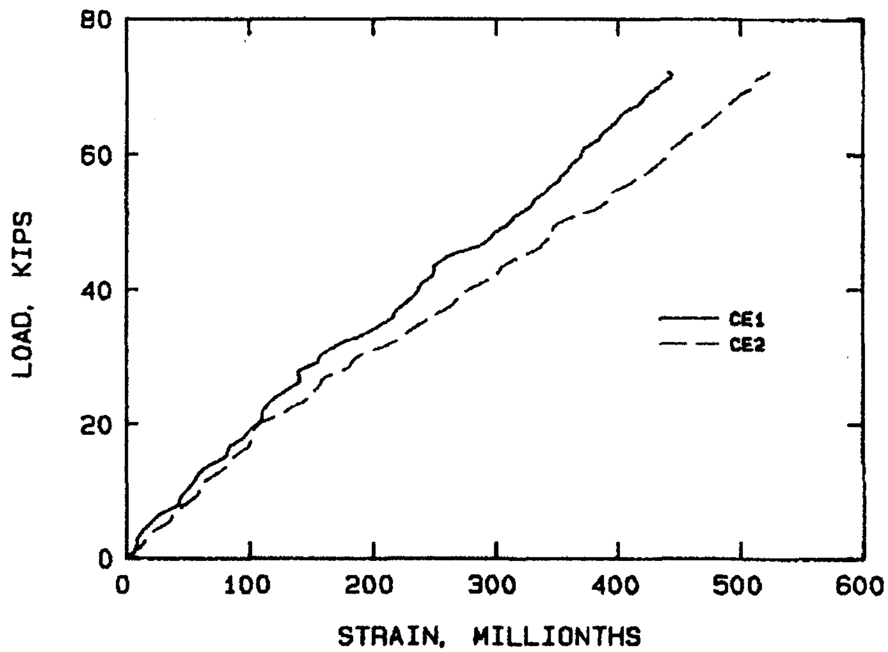

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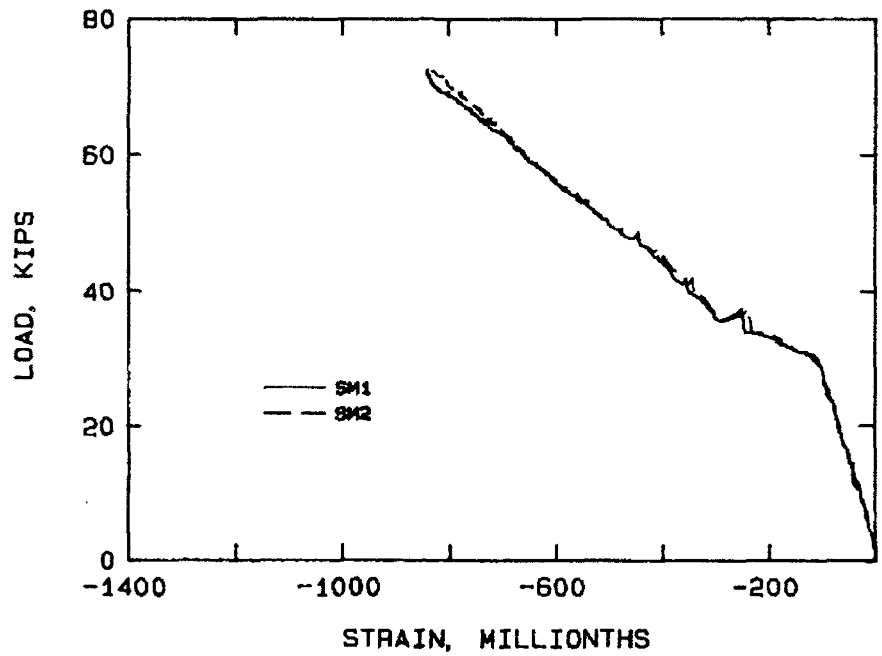

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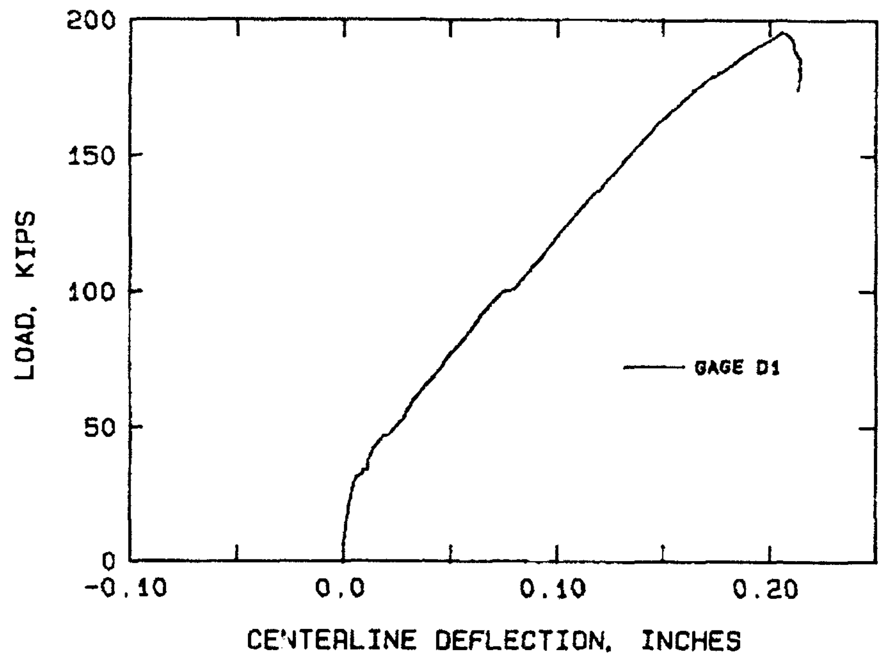
-200
STRAIN, MILLIONTHS
SM1
SM2

Figure B5

Appendix C
Data Plots, Beam R2



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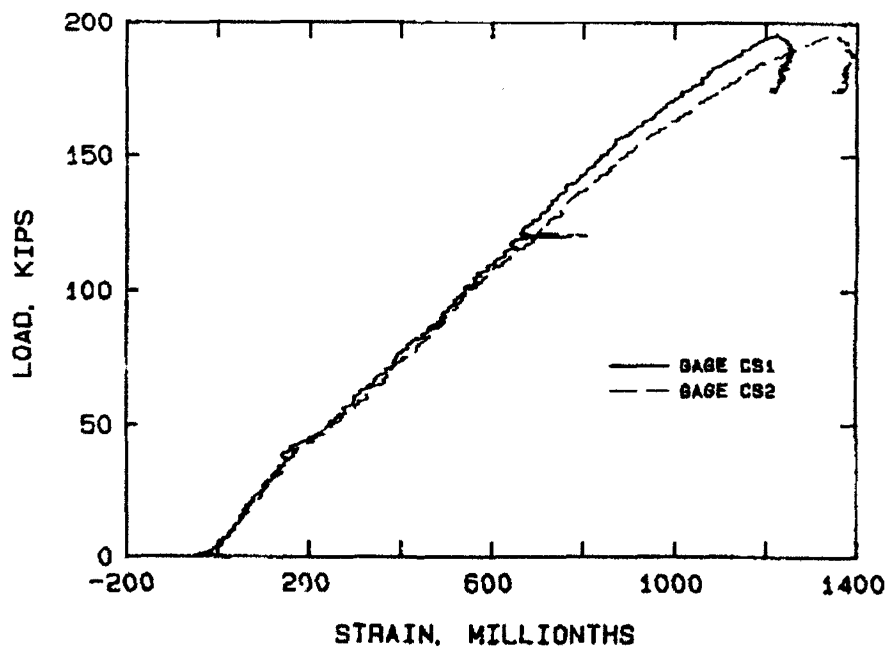

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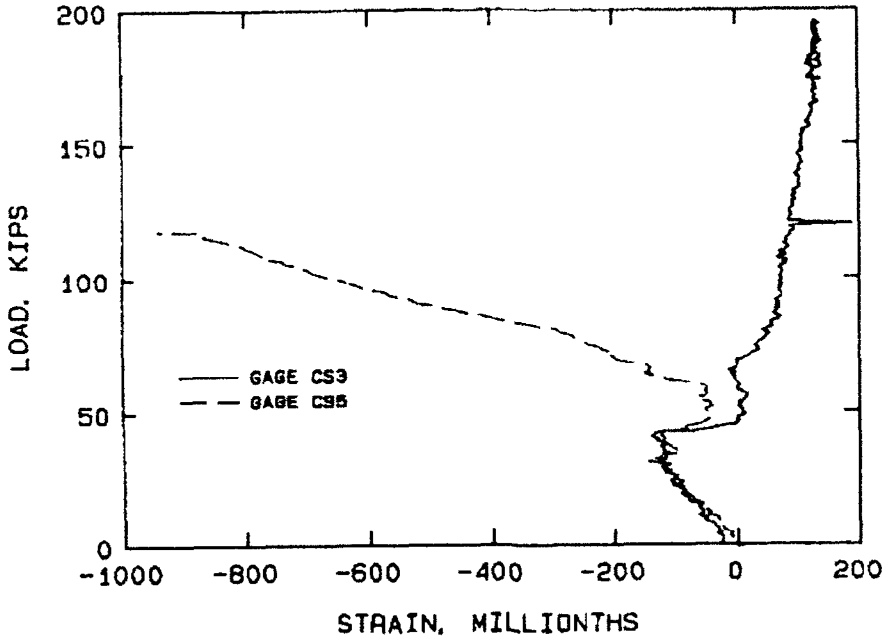

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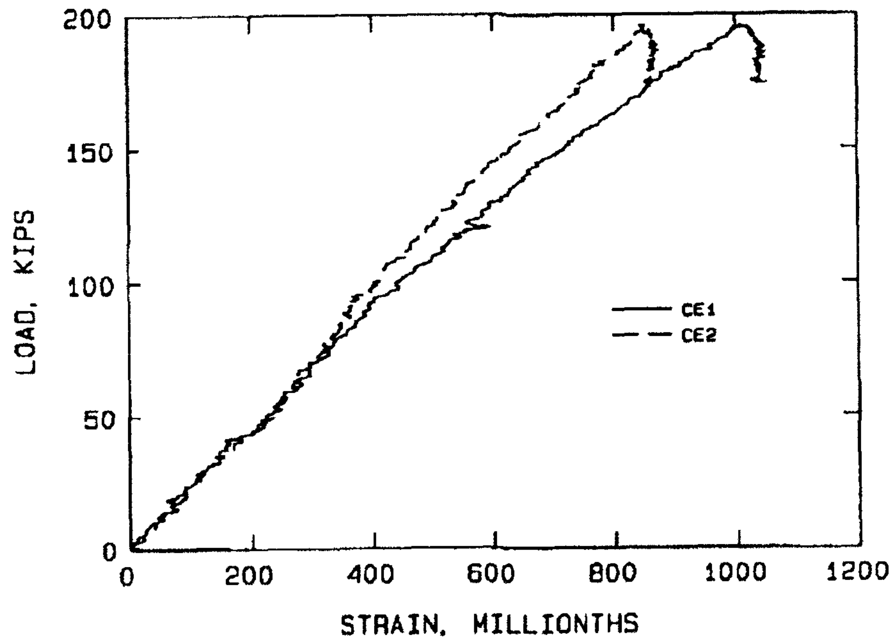

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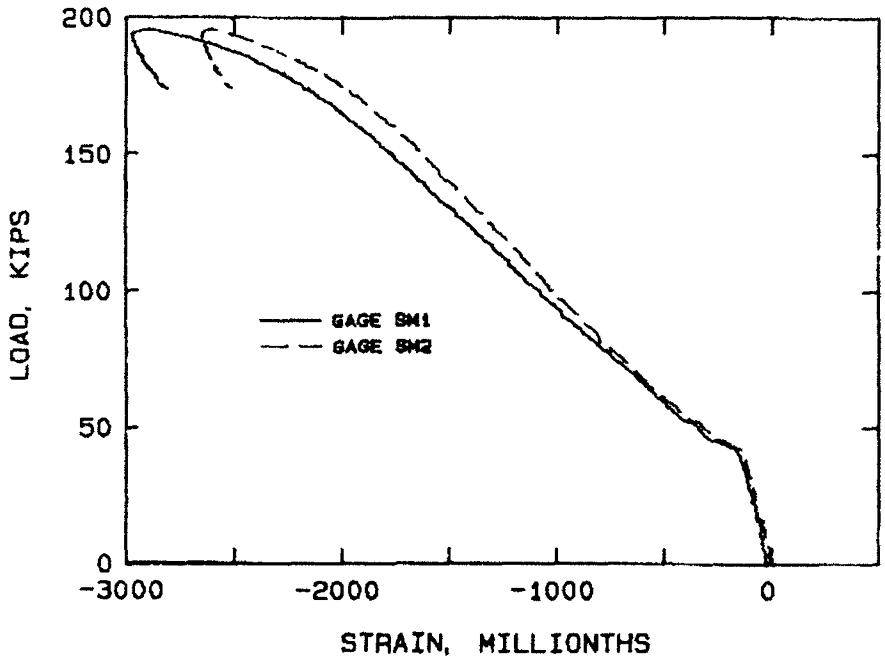

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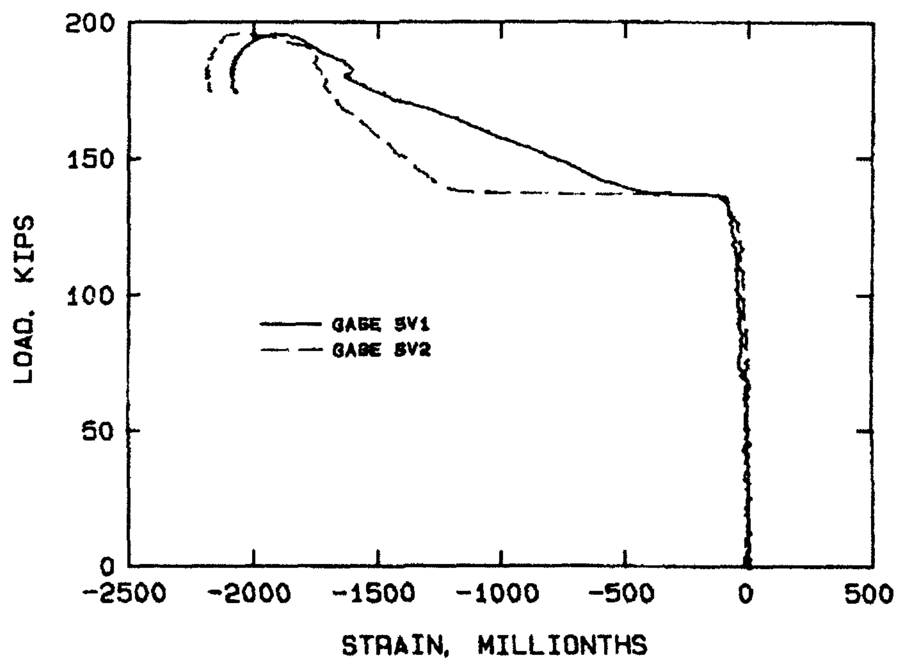
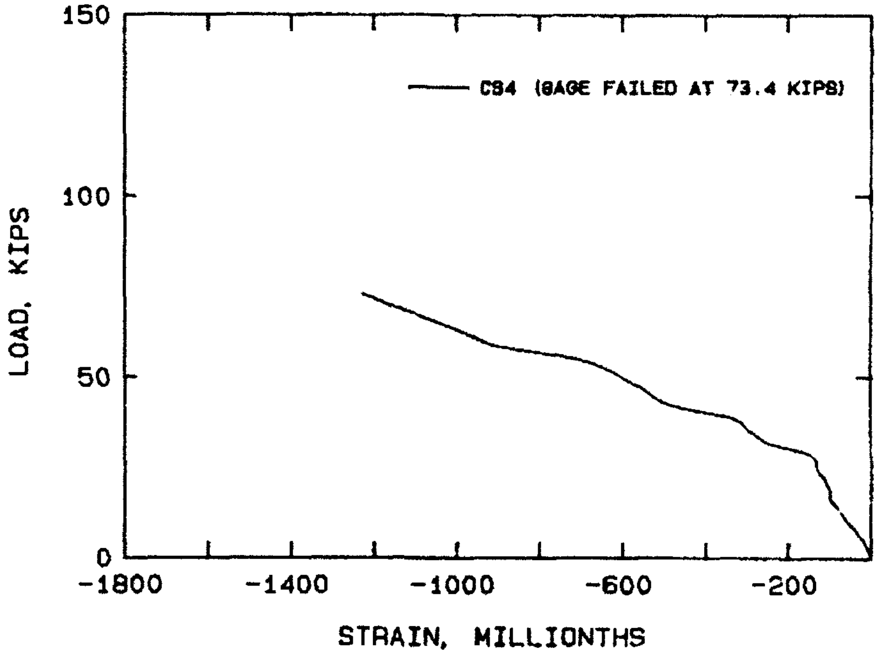


Figure C6

Appendix D
Data Plots, Beam RS1



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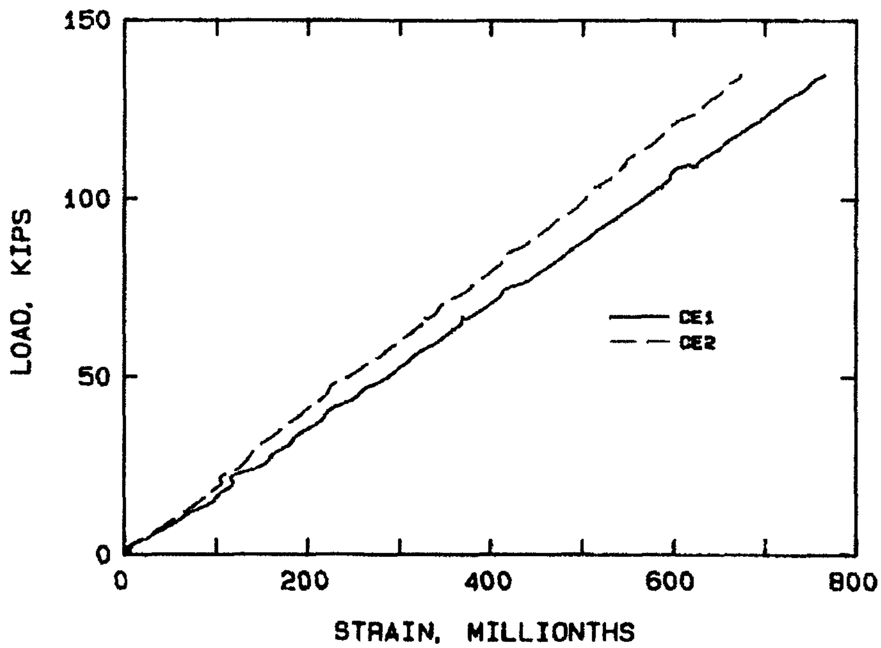

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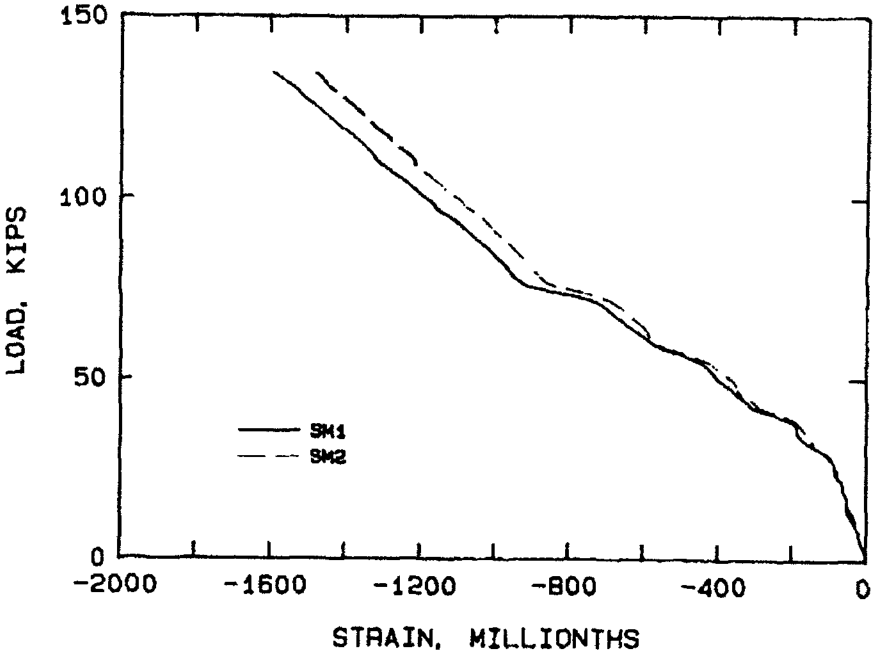

150
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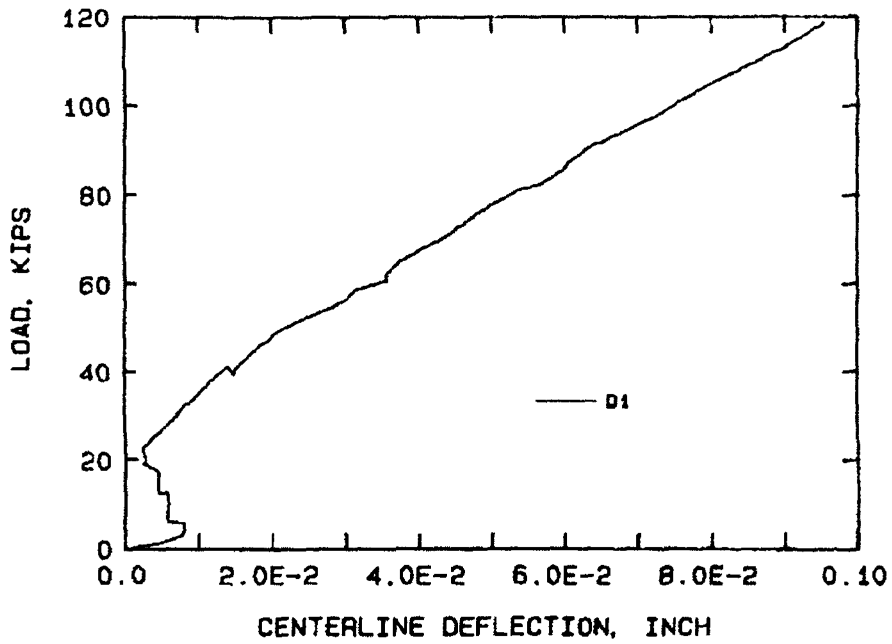
LOAD, KIPS
STRAIN, MILLIONTHS
SM1
SM2

Figure D3

Appendix E
Data Plots, Beam RS2



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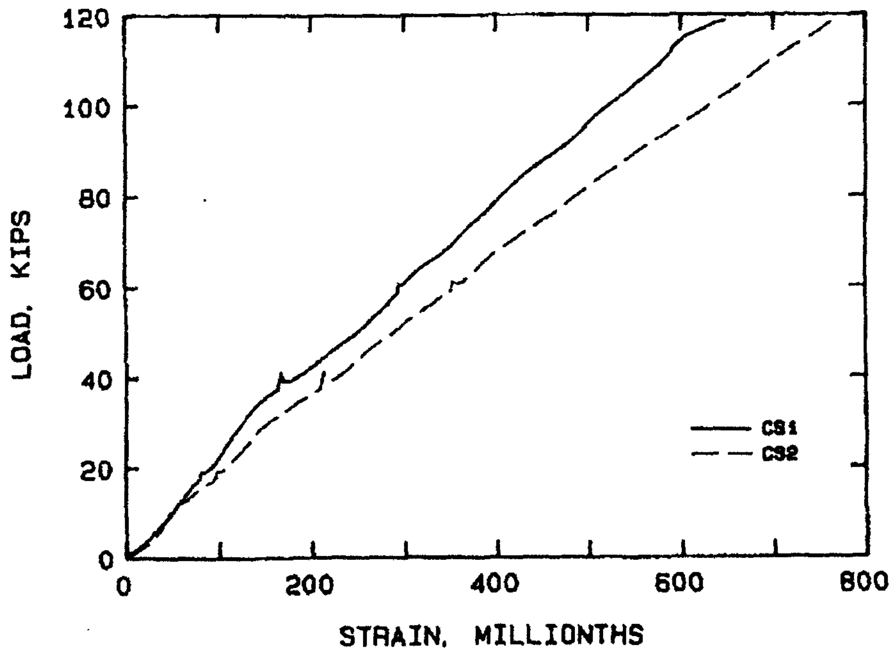

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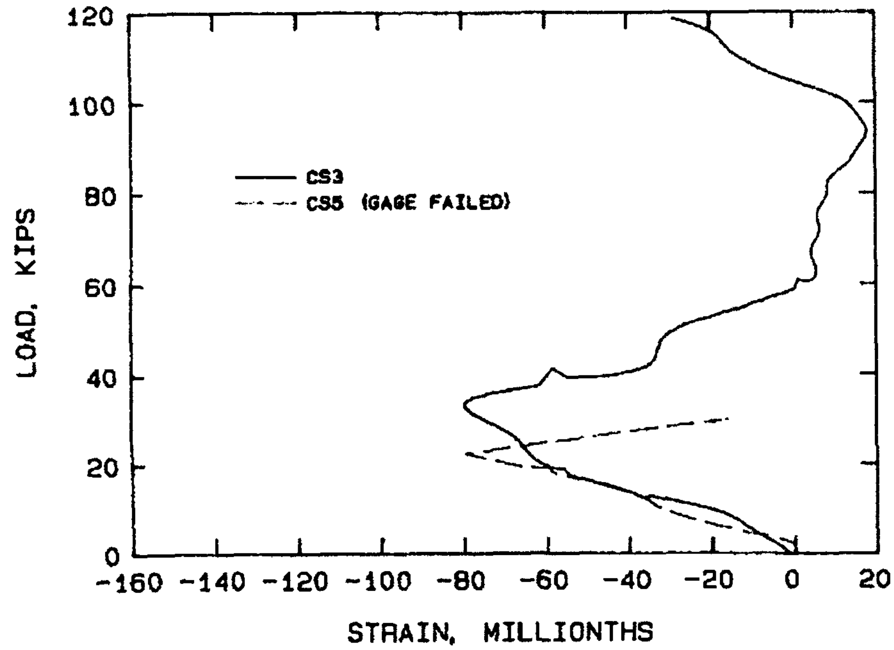

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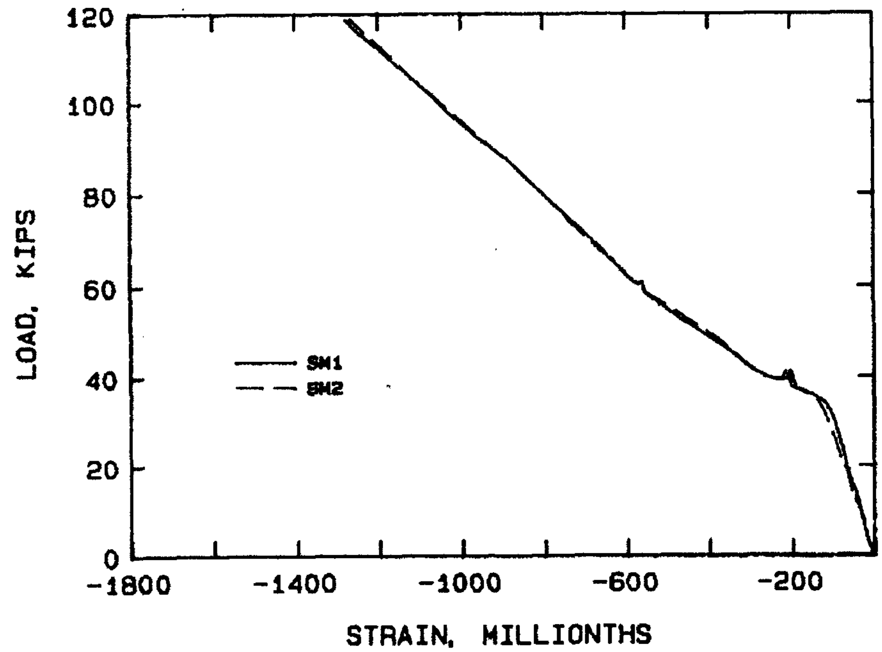

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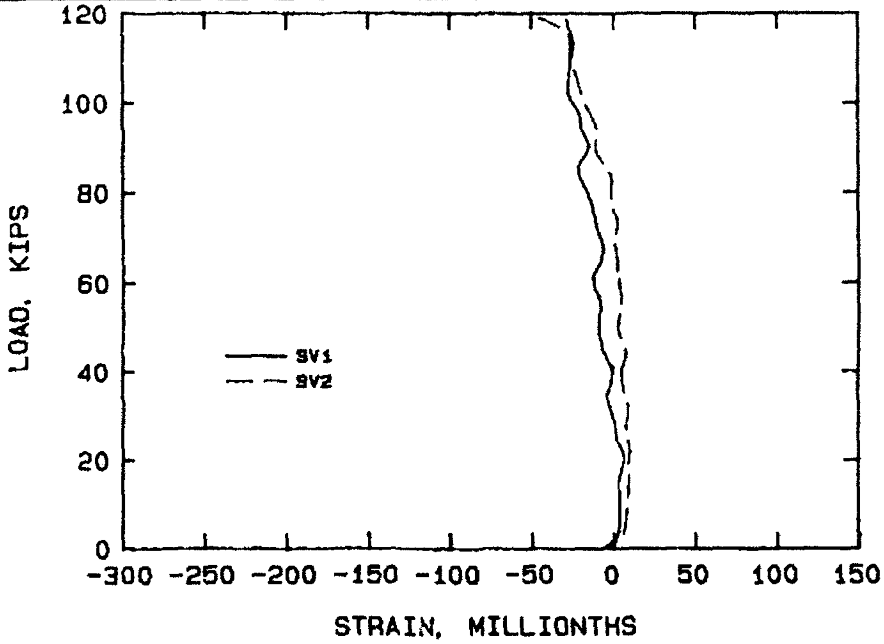
LOAD, KIPS
STRAIN, MILLIONTHS
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-300 -250 -200 -150 -100 -50 0 50 100 150

Figure E5

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1993

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Investigation of Modified Sulfur Concrete as a Structural Material

5. FUNDING NUMBERS

6. AUTHOR(S)
Michael I. Hammons, Donald M. Smith, Dan E. Wilson, C. Scott Reece

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAEWES
Structures Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

National Chempruf, Inc.
1751 Jarcko Drive
Clarksville, TN 37041

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report CPAR-SL-93-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Industrial applications of modified sulfur concrete (MSC) have been extremely successful in areas of high corrosive activity such as load-bearing floors, walls, and sumps of chemical plants. However, there have been no research and development efforts involving the use of this high-strength, corrosion-resistant material in the very demanding structural component field. Designers require extensive structural test results to establish the confidence necessary to specify MSC as a structural material in any major structure. The objective of this study was to determine the applicability of MSC to the construction and repair of structural components and load bearing surfaces. A series of tests were conducted on MSC to determine mechanical properties important to structural design, freezing-and-thawing performance data, bonding of MSC to portland-cement concrete (PCC), and a series of limited reinforced MSC beam tests to compare with PCC structural design criteria. In general, MSC behaves similarly to a PCC with a comparable compressive strength. The modulus of elasticity and Poisson's ratio of MSC are comparable in magnitude to that of a PCC of comparable strength. Beam tests indicate that MSC appears to conform to the basic assumptions of reinforced concrete beam design including the formation of an effective moment-resisting couple. The ductility of MSC in the postyield regime, however, has not been determined in these tests.

14. SUBJECT TERMS

Bond strength	Modified sulfur concrete	Strength design
Compressive strength	Modulus of elasticity	Structural design
Freezing-and-thawing durability	Repair	Tensile strength

15. NUMBER OF PAGES
62

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	